CSM was started in 1963, as CORPORATE research centre of FINSIDER (nationalized steelmaking corporation). CSM experience on Electrical Steel started at beginning of 70’s of last century, in cooperation with Finsider Terni Plant,
Nationalized steelmaking industry was privatized in 1994, so it was CSM.

CSM nowadays is a fully private innovation center with extensive experiences for the development of materials and relative production processes. WITH A WIDE EXPERIENCE IN ELECTRICAL STEEL. It is part of RINA Group, which is a global provider of classification, certification, testing, inspection and training services.

Few weeks ago CSM joined other Rina technological services companies under the new brand RINA CONSULTING
Since privatization CSM has been cooperating in the field of Electrical steel with several steel producers, plants manufacturers, and end users.

**Producers:**
- Nippon Steel
- ThyssenKrupp Electrical Steel
- APERAM SA
- Tata Steel Europe
- VoestAlpine Stahl
- Erdemir RO
- Acroni
- Acciaieria Arvedi
- National Metallurgical Laboratory (India)

**Plant Manufacturers**
- Tenova LOI
- Tenova Italimpianti
- Danieli
- ABB
- Siemens-VAI
- MECON Limited

**End users**
- Energy utilities
- Transformers Manufacturer
- Italian Ministry of defence
- motors manufacturer
- Magnetic shielding manufacturer
Improvement of Electrical steels products and relative production technologies
Summary

- Theoretical introduction to FeSi Magnetic characteristics and their relation with microstructural features
- Improvement of GO material
- Improvement of NGO materials
- Conclusions
Electrical steel the main “raw material” magnetic core of electric machines manufacturing.

Differently from major part of steels, it is used because of its magnetic properties, more than because of its mechanical properties.

- **POWER LOSSES:** $P$  
  (efficiency of electric machine)

- **POLARIZATION:** $J$  
  (size of the electric machine)
Characteristics curves

GO measured along RD
NGO measured along RD+TD

Better materials
Smaller magnetic core at same nominal power

Better materials
More efficient electric machine
Characteristics curves

- J800
- J2500, J5000, J10000
- P10, P15
- P15, P17

Polarization vs. Magnetic Field
Losses vs. Polarization
Magnetic anisotropy

P [w/kg]

NGO Fe-1%Si
0.65 mm

NGO Fe-2%Si
0.50 mm

NGO Fe-3%Si
0.35 mm

GO Fe-3%Si
0.30 mm

RD
Electrical steel: Crystallography

**Grain Oriented**

**Non grain oriented**
Orientation of the grains lattice is very close to “ideal” Goss orientation: <001> direction parallel to rolling direction
{110} plane parallel to the rolling plane
Electrical steels: Microstructure

**Grain Oriented**

Non grain oriented

**Fully finished: Si+Al :1,2%**

Non grain oriented

**Fully finished: Si+Al :4%**

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The magnetic domains structure is determined by the “exchange interaction”, which aligns each other the magnetic moments of the iron atoms, and aligns them with $<100>$ crystallographic direction.
Magnetic losses

\[ P = Ph + Pcl + Pan \]

- **Ph**: hysteresis
- **Pcl**: classical
- **Pan**: anomalous

![Graph showing magnetic losses with different loss components](image)
**Magnetic losses: hysteresis**

\[ P = P_h + P_{cl} + P_{an} \]

**Ph: hysteresis**

It depends on the lattice defects (precipitates, grain boundaries in the material, which hinder the evolution of magnetic domains during the magnetization process.)

\[ P = P_{hysteresis} + P_{cl} + P_{an} \]

\[ H=0 \]

\[ H=H_1 \]

**PRECIPITATES**

\[ H=0 \]

\[ H=H_1 \]
Magnetic losses: Classical «eddy current»

\[ P = \Phi_h + P_{cl} + P_{an} \]

**Pcl:** classical (eddy current)

Is. The power loss due to the macroscopic electric current induced by the variation of magnetic induction field (Foucault current)

\[ I \propto \frac{d\Phi(B)}{dt} \]

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$P = P_h + P_{Cl} + Pan$

Pan: anomalous

It is the excess loss, i.e. the loss term accounting for the presence and the motion of magnetic domains walls during alternate magnetization process.
According to Bertotti Model:

\[
L_{Iron} = L_h f + \frac{\pi d^2}{6} \left( B_{\text{max}} f \right)^2 \rho + 3 \left( B_{\text{max}} f \right)^{3/2} \sqrt{\frac{GSV_0}{\rho}}
\]
The magnetic polarization depends:
1) On the chemical composition: higher is the Fe concentration higher is the polarization

2) on the allignement of applied magnetic fileld with the easy magnetization direction <100>
In case of GO an increasing of the grains alignment increases the polarization at 800 A/M (J800).
Magnetic polarization: NGO

In case of NGO the grains orientation which increase the magnetic polarization are the ones for which \(<100>\) direction is aligned with the rolling plane.

Favourable orientations

Unfavourable orientations
Grain Oriented Grades

ES world production: \( \approx 13-14 \) MI tons/year
(1-2% of the world production of flat steels)

\[ \downarrow \]

GOES grades
(\( \approx 2-3 \) MI tons/year)

CGO
(conventional grades)

\[ \leftarrow \]

HGO
(high permeability grades)
In the last years the improvements in GO products have regarded the **reduction in thickness** (reduction of eddy current) and the **Laser scribing** (reduction of anomalous losses).
Lower thickness for improving core losses

Conventional thickness HGO products

Low thickness (0.18 mm) HGO
GO production cycles are quite long and complex. They require an extremely strict control of process parameters, higher than what usually done in other iron and steel products.

Key step is the reheating of the slab at unconventionally high temperature (1400°C) to form the precipitates necessary to produce the Goss grains (secondary recrystallization).

Secondary recrystallization happens during final batch annealing, during which the secondary recrystallization happens, which produces Goss Grains.
Secondary recrystallization metallurgy:

$1000^\circ\text{C} - 1100^\circ\text{C}$

$10^\circ\text{C/h}$
Secondary recrystallization metallurgy:

Temperature range: 900 - 1100°C

Cooling rate: 10°C/h to 1200°C
Secondary recrystallization metallurgy:

The phenomenon

$900 - 1100^\circ C$

$10^\circ C/h$

$900 - 1100^\circ C$

$10^\circ C/h$

RD
Secondary recrystallization metallurgy:

Temperature range: 900 - 1100°C

Cooling rate: 10°C/h
Secondary recrystallization metallurgy:

- The phenomenon

\[ T = 900 - 1100 \degree C \]

\[ 10 \degree C/h \]

\[ t \]

\[ RD \]
Secondary recrystallization metallurgy:

The phenomenon

$900-1100^\circ C$

$10^\circ C/h$

$0-900^\circ C$

$10^\circ C/h$
Secondary recrystallization metallurgy:

The phenomenon of secondary recrystallization typically occurs in the temperature range of 900-1100°C. This process is characterized by a cooling rate of 10°C/h.
In order to better control secondary recrystallization in the recent years new technology was developed in which instead of reheating the slab at high temperature, ammonia is injected in the last part of decarburization annealing to induce nitrides precipitation.

The better control of secondary recrystallization, has allowed the development of thinner grades (0.18mm).
Going to Low Thickness...
To which extent is possible? ... and convenient?
Lancet domains structure presented through the sheet thickness (scheme on the LEFT) and how they appear from surface (photo on the RIGHT)
Magnetic properties

Surface Structure of GO sheet

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Magnetic properties:
Developments for superior magnetic quality

Smaller surfaces + optimized tension coatings

conventional:

new:
smooth surface + optimum tension coating

Phosphate coating e.g. 3 µm
Glass-film

1 µm

230 µm

intermediate coating layer
Laser scribing

LASER:
CO₂ Type, = 10.6 [μm]
P_{max} = 1200 [W]

Rotating
Mirror:
N_{mirr} = 12

Plain Mirror

Concave or Plain Mirror

V (lines) = 30 [m/min]

300 [mm]
Laser scribing: effect

\[ P = P_h + P_{Cl} + P_{an} \]

Pan: anomalous

It is the excess loss, i.e. the loss term accounting for the presence and the motion of magnetic domains walls during alternate magnetization process.
Non-grain oriented
Resistivity increasing (Alloying)

Alloying with Si, Al, Mn has a positive effect on Eddy current and Anomalous losses
On the other side alloying has a negative effect on polarization, moreover Si and Al provoke embrittlement which creates problems in cold rolling and stamping.

So it is a matter of finding the right compromise. Commercial products have a maximum Si concentration of 3.0-3.2% and maximum Aluminum of 1-1.2% Maximum Mn is typically 0.5%.
Reduction of precipitates

\[ L_{\text{Iron}} = L_h f + \frac{\pi d^2}{6} \frac{(B_{\text{max}} f)^2}{\rho} + 8(B_{\text{max}} f)^{3/2} \sqrt{\frac{GSV_0}{\rho}} \]

hysteresys

Fig. 2: Influences of sulphur, oxygen and nitrogen contents on core loss of non-oriented 3% silicon steel.

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Reduction of precipitates reduces hysteresis losses and also increases the polarization, which can have a big impact on the material characteristics.

In the last 20 years the improvements in primary steelmaking processes (liquid steel treatment) has allowed to produce FeSi very clean from precipitates, which has allowed to develop new products (M250-50A, M230-50 A, M210-50A). And also to produce grades with lower alloying and improving the polarizability.
Reduction in thickness is a key factor for high frequency application. It influences the «eddy current» losses, which depend on the square of thickness and on the square of frequency

\[
L_{Iron} = L_h f + \frac{\pi d^2}{6 \rho} (B_{\text{max}} f)^2 + 8 (B_{\text{max}} f)^{\frac{3}{2}} \sqrt{\frac{GSV_0}{\rho}}
\]

Until few years ago the minimum available thickness was 0,35 mm, nowadays 0,20 mm or lower can be found for High frequency application.
The increasing of fraction of grains with favourable orientation (<100> direction parallel to the lamination plane), increases the polarization of the material.
Improvement in grains orientation

From the process point of view the increasing of favourable Orientation can be reached

- Performing Hot rolled strip annealing

- Properly optimizing the hot rolling procedure

This increases the favourably oriented grains in hot rolled strips, which increases the favourable grains nuclei after cold rolling, which are able to produce properly oriented grains after annealing.
Better grains orientation: higher permeability product
Grain size optimization

Optimal grain size Grain size depend on the frequency of the application

\[ L_{Iron} = L_h f + \frac{\pi}{6} \frac{d^2}{\rho} (B_{max} f)^2 + \frac{8(B_{max} f)^{3/2}}{\rho} \sqrt{\frac{GSV_0}{\rho}} \]
New and high performance Electrical Steels have been developed in the last years and are under development:

• GO: low thickness and smooth surface, new coatings, optimized laser scribing.

• NGO: ultra-clean steels, low thickness for high frequency application, high permeability materials.

Available high performance materials is allowing a further improvement of efficiency of electric machines
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