MOGOCA EVO

Metallurgical Model Of Grain Oriented High Temperature Coil Annealing

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Our experience. Your growth.

MOGOCA-EVO is a process-oriented, user-friendly, PC-based metallurgical tool designed for grain growth control in Grain Oriented (GO) technology. It is intended for experts in production, quality, and research and is open to further integrations.

The availability of a simulation tool capable of describing the basic processes and microstructure evolution during the High Temperature Coil Annealing (HTCA) of GO Electrical Steel (ES) has been a very urgent need for many years within the relevant industrial and scientific communities. However, due to the enormous complexity of the phenomena involved and the numerous technical parameters that influence the results, achieving this objective required continuous field experience and careful experimentation. [1][2]

A mathematical tool (MOGOCA) was presented to investigate in detail the kinetics of the stability of grain growth inhibitors (second phase particles, e.g., nitrides) and to evaluate the oxidation kinetics of aluminium on the strip surface and its effects on precipitate stability and glass film formation. An important step has been made with the MOGOCA-EVO comprehensive tool, introducing a secondary recrystallisation (SRX) module.

This module, considering microstructure and texture in the primary recrystallised stage (grain size, grain heterogeneity, texture), can handle the entire microstructure evolution in HTCA and predict the final magnetic properties (magnetic induction, B800) and the secondary grain size.

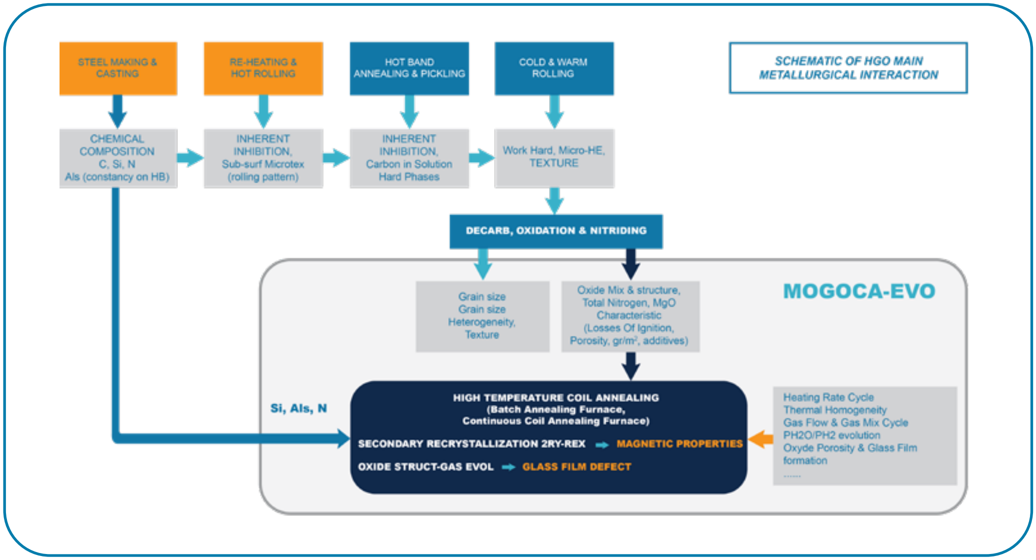


Figure 1 - Schematic view of the HGO main metallurgical interaction and work area of the MOGOCA-EVO software.

Ways and **Means**

- Thermodynamics and kinetics models in the solid state (diffusion of elements, precipitate dissolution and growth, grain growth stability)
- Models of steel surface interaction of gases and gas permeability through porous media (MgO) and surface oxide layer
- Application of dilution law applied to gas dilution in the furnace inner cover (by mass flow) and for dilution through MgO into coil inter-spire gap (by gas diffusion)
- Evaluation of final properties (magnetic induction B800, grain size) as a function of metallurgical and process parameters

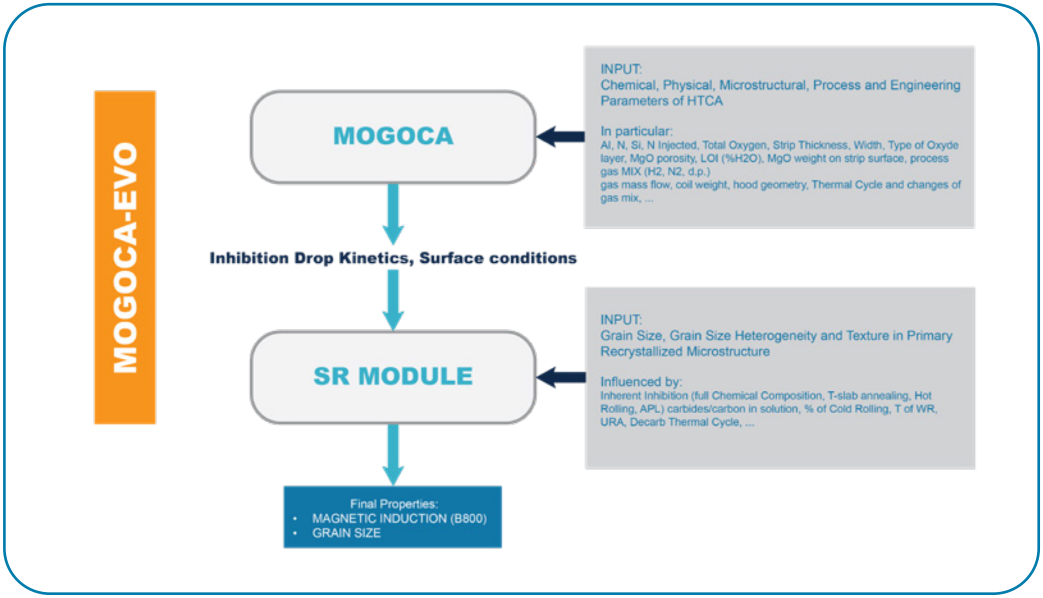
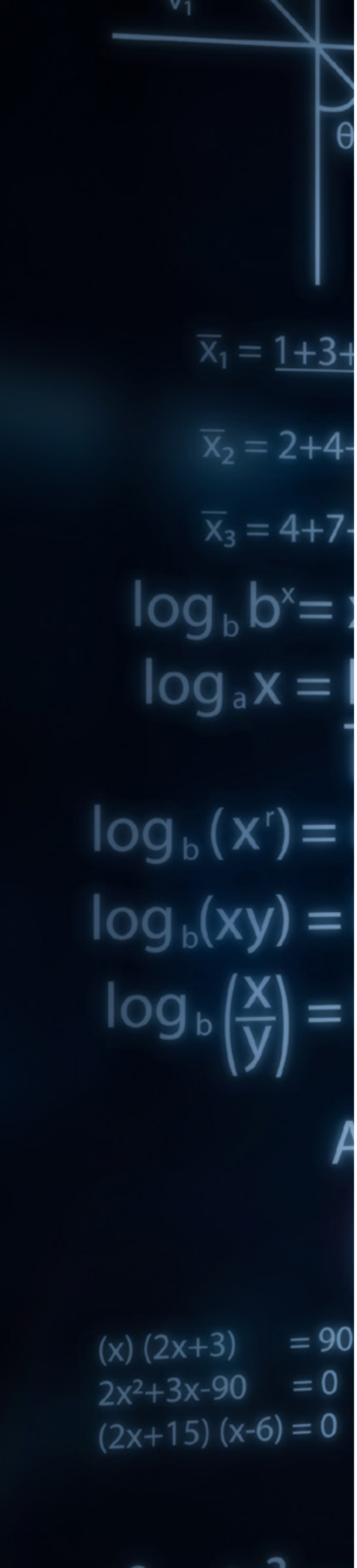


Figure 2 - Outline of the MOGOCA-EVO modules.



- MOG-App: software to simulate the diffusion phenomena and inhibition evolution during High Temperature Coil Annealing (HTCA)
- GOTEX-App: module to evaluate the microstructure of the final grain size and to simulate the magnetic properties (B800) of the final product (HGO) after HTCA

INPUT (MOG-App)

- Strip thickness, coil width, furnace inner cover technical parameters (engineering/ geometrical)
- Silicon content, aluminium, inherent nitrogen, injected nitrogen
- Thermal cycle and process gases type (H_2, N_2, H_2O) in the furnace (heating rate and process gas mix at different heating phases/soakings, gas mass flow at each phase)
- Surface barrier of oxide layers to nitrogen penetration
- Total oxygen after the decarburisation process

OUTPUT (MOG-App)

Metallurgical evaluation

- AlN precipitate stability through the strip thickness and at different coil heights
- Grain growth inhibition evolution at different distances from the strip surface and coil heights
- Critical conditions for secondary recrystallisation evolution
- Dew point and PH_2O/PH_2 ratio between the spires at different coil heights (oxidation/ reduction condition)
- Nitrogen purification efficiency
- Estimation of glass film damage
- Sensitivity analysis of the various process and metallurgical parameters adopted (process control)
- Process optimisation and new cycle design (product metallurgy, production efficiency)

Physical and chemical data

- AlN and Si_3N_4 product solubility
- Nitrogen solubility in Fe-Si surface as a function of gas pressure
- Diffusion coefficient in solid state (Al, Si, N)
- Gas diffusion coefficients (N_2, H_2, H_2O)
- MgO particle distribution (Porosity)

INPUT (GOTEX-App)

- Grain size, grain size heterogeneity, and Texture in the primary recrystallized microstructure
- Chemical composition, inhibition drop Kinetics (from Mog-App)

OUTPUT (GOTEX-App)

- Magnetic induction (B800) evolution
- Final grain size after secondary recrystallisation

Evolution of **precipitates through the thickness**

The final magnetic properties, including the secondary grain size effect, are significantly modulated by how grain growth inhibitors lose their restraining force, either through particle dissolution or the Ostwald ripening process, along the thermal cycle. The average inhibition strength, Iz, is well characterised by the following formula:

$$I_z = \frac{6}{\pi}\frac{f_v}{r}$$

Where fv = volume fraction of precipitates and r = average size of the particles.

Both the parameters fv and r (volume fraction and mean radius) are affected by the thermal treatment, the first mainly by dissolution of precipitates while the second mainly by Ostwald ripening. They both also cause a reduction in Iz following different physical paths. The evolution through thickness (GO steel 0.23mm) of aluminium, total and in solution, nitrogen in solution, and precipitates (AIN) at different temperatures during HTCA can be calculated by the MOGOCA-EVO software (see Figure 3).

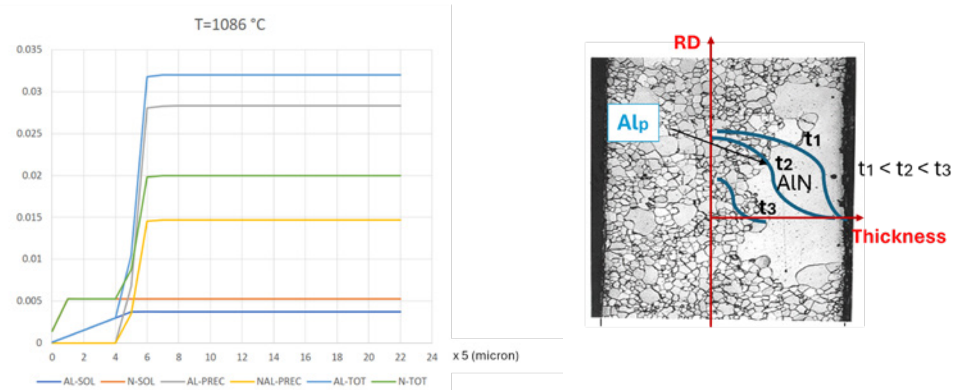
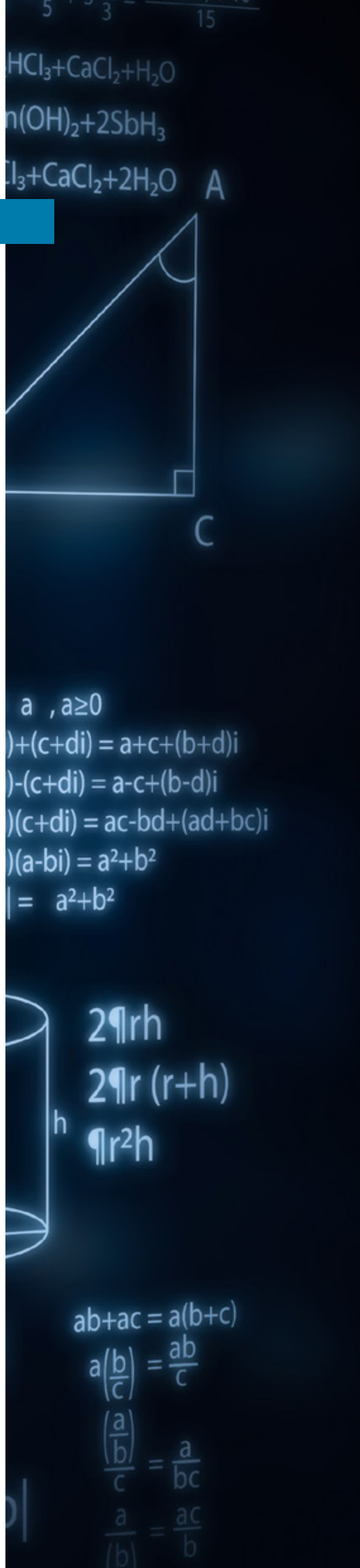


Figure 3 - Examples of the evolution through thickness (0.23mm) of aluminium (total and in solution), nitrogen (total and in solution), and Al and N as AlN, at T=1086°C during HTCA.



Evolution of the **inhibition strength Iz during HTCA**

The drop in inhibition strength at high temperatures is a heterogeneous process along the strip thickness due to the oxidation of aluminium on the strip surface, where less thermodynamically stable oxides are present (SiO2, Fe2SiO4 as opposed to Al2O3). Curves showing the inhibition kinetics during HTCA at different thickness depths can be calculated using the MOGOCA-EVO software. In Figure 4, an example of curves calculated by this software is shown, predicting the evolution of the inhibition strength, Iz, during HTCA as a function of the nitrogen content. A set of Iz curves are shown for nitrogen content between 120 and 330 ppm as an example of the software's application.

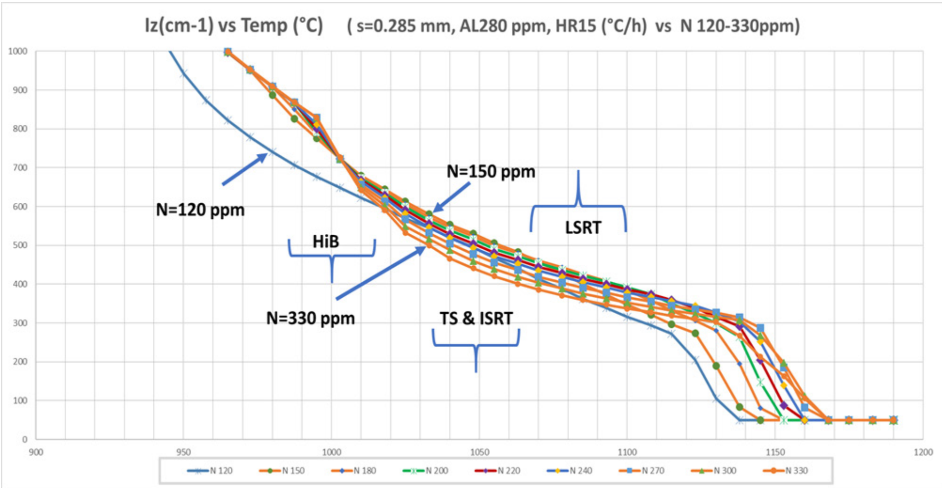


Figure 4 - Inhibition strength (Iz) evolution vs temperature (following the heating rate in HTCA) with nitrogen content as a parameter - A set of Iz curves are shown in case of nitrogen content between 120 and 330 ppm.

Magnetic map of **B800**

As a significant example of a tool that can be generated by MOGOCA-EVO to analyse and optimise the practical results of the specific technology adopted, a two-dimensional magnetic map is shown below, where B800 is plotted as a function of total nitrogen and primary grain size at the start of the HTCA cycle.

ICPT (µm) 12.7	15.3	17.8	19.1	20.4	22.9	24.2	25.5	26.7	28.0	NITROGEN (ppm)
1662	1691	1737	1762	1764	1817	1817	1828	1794	1738	90
1903	1910	1901	1864	1867	1910	1867	1854	1795	1751	120
1909	1919	1901	1901	1904	1896	1905	1895	1876	1727	140
1909	1919	1913	1913	1914	1910	1869	1909	1800	1701	150
1909	1917	1925	1926	1918	1919	1917	1902	1781	1737	180
1908	1918	1923	1933	1929	1920	1921	1899	1879	1695	200
1867	1916	1921	1931	1935	1922	1923	1910	1845	1703	220
1869	1914	1919	1929	1926	1938	1933	1920	1718	1719	240
1816	1912	1916	1925	1922	1936	1940	1934	1730	1636	270
1764	1853	1909	1910	1918	1931	1940	1940	1905	1715	300
1719	1757	1912	1907	1920	1920	1930	1940	1925	1698	330

Figure 5 - Magnetic map (B800) by metallurgical and process parameters - The colours in the map represent at a glance homogeneous zones of B800 results and can be read as follows: dark red=unacceptable, red=bad, orange=insufficient, light greens=sufficient, dark green=good, blue=very good.

n- dimensional space

A series of B800 maps can be obtained alternating the various relevant parameters for magnetic properties and moving them on the axes for the results optimisation. The comprehensive map would be a multidimensional plot, as illustrated in Figure 6, where each axis represents a parameter contributing to the refinement of the n-dimensional surface optimisation. MOGOCA-EVO runs efficiently on a laptop computer, enabling rapid scans of the influence of the parameters under investigation. Its versatility and user-friendly interface make it a practical tool for the industrial world.

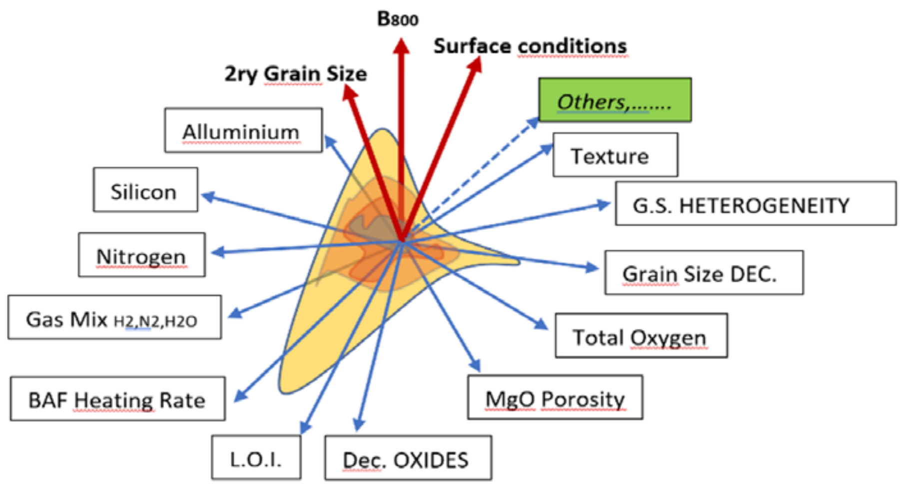


Figure 6 - N-dimensional optimisation surface for magnetic properties generated by the various relevant parameters in GOES Technology.

References

- [1] G. Abbruzzese - Metallurgical model of high temperature coil annealing in GOES Production, Proc. WMM Dresden 12th - 14th June 2018, ISBN 978-3-86012-579-3. Pages 630-649
- [2] G. Abbruzzese - Metallurgical Model of HTCA for GO Silicon Steel with prevision of Magnetic Properties (B800) and Secondary Grain Size (MOGOCA-EVO - Proceedings of 9th-WMM2020-Rome, November 2020, ISBN978-88-900033-1-8, pp117-135

Notes

The MOGOCA-EVO software tool represents the most suitable solution for supporting and addressing all research efforts towards anticipated developments (products, processes, and plants), as well as a practical tool for ongoing quality enhancement and production optimisation.

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