General Overview on **ST**abilized **EL**ectrical **S**teels for **E**lectric **M**obility Project

(**STeELS-EM**)

(RFCS Project Number 101034063)

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Abstract

The main objective of the project is to develop new fully stabilized non grain oriented (NGO) electrical steel, where the interstitial elements are bound to coarse particles and where the formation of fine precipitation is strongly reduced. As a matter of fact, fine particles are deleterious for the magnetic quality of electrical steels, as they negatively interact with grain growth, preventing the formation of an optimal microstructure. At the same time, they directly and adversely interfere with the magnetization processes, pinning the magnetic domains walls. Such a pinning deteriorates magnetic quality, by increasing core losses ($P_{15/50}$, $P_{10/400}$) and decreasing polarization (J_{2500}, J_{5000}, J_{10000}). The project target is expected to be obtained by using unconventional chemical compositions of the alloy characterized by higher concentrations of Ti, Nb or V to promote the scavenging of N and C from the ferritic matrix and coarsening of the precipitates. The study, still in progress, is expected to improve the control of precipitation and texture development in NGO electrical steels, by exploiting the predictive capabilities of thermodynamic and kinetic modelling of available commercial packages (ThermoCalc, MatCalc, JMatPro). This in turn allows us to refine the alloy design for NGO electrical steels, as well as to predict the chemical composition of precipitates and their evolution as a function of the production cycle of the steel. In this contribution the main results at the present stage of the project are summarized.

Introduction

The overview of the project is shown in **Error! Reference source not found.**: here the project structure is described in terms of eight different work packages (WP), and their interactions. Figure 2 shows the consortium of beneficiaries: RINA-CSM (Italy, coordinator), Voestalpine (Austria), Gent University (Belgium), OCAS (Belgium), RWTH Aachen (Germany).

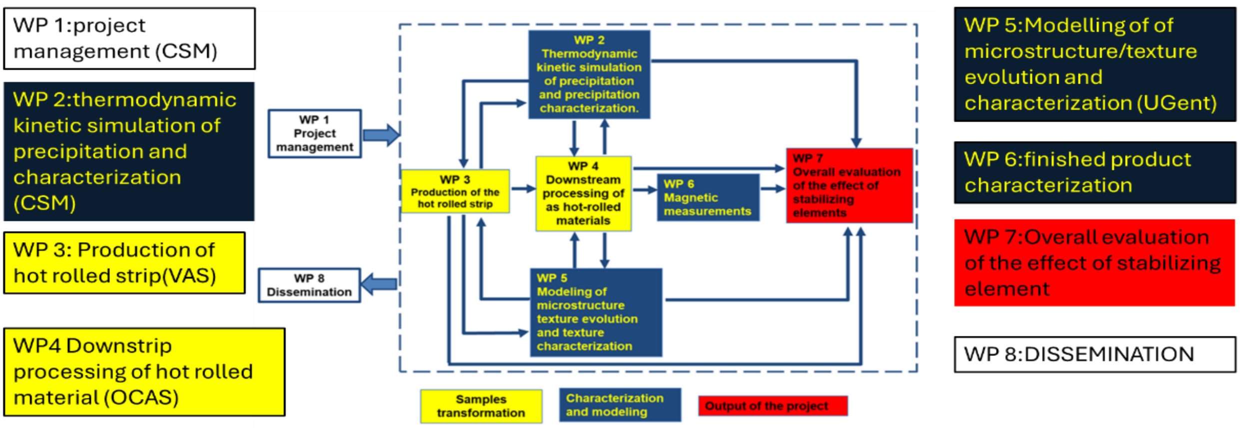

Figure 1 SteELS-EM Project Work Packages and schematic of their interaction.

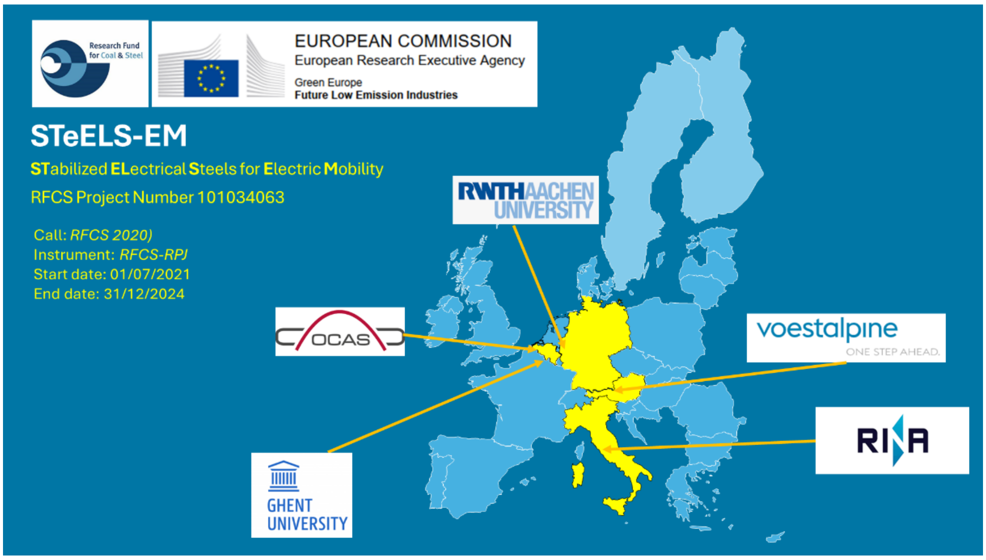

Figure 2 Overview of STeELS-EM Project beneficiaries: RINA-CSM (Italy), Voestalpine (Austria), Gent University (Belgium), OCAS (Belgium), RWTH Aachen (Germany)

Thermodynamic/kinetic simulation of precipitation and precipitation characterization

Four different chemical compositions, represented in Table 1, were tested, in total, in this initial phase of the project. Such chemical compositions have been defined as "reference". These represent the typical chemical compositions used in the "State of art" of industrial production with two levels of silicon: 1% (low Si) and 3% (high Si). In addition, the following (Si+Al) % amount of 2.04 % and 3.90 % respectively for low Si and High Si case have been considered. This choice is related to the occurrence of the $\alpha \rightarrow \gamma \rightarrow \alpha$ phase transformation during hot rolling, which happens when (Si + Al) is low, and which is suppressed for high (Si + Al). This transformation also influences the texture development of materials, thus giving the opportunity to modulate the texture and to promote the magnetically promising texture components.
In the reference compositions the stabilizing elements have been kept low according to what is typically done in standard industrial production.

Thermodynamic commercial models (ThermoCalc [1], MatCalc [2], JMatPro [3]) have been used to predict and compare the equilibrium fraction and chemical composition of the main precipitating phases. All of them rely on the CALPHAD [4] approach for describing the chemical equilibria in terms of Gibbs free energy curves of the different phases involved in the equilibria. Regarding the precipitation kinetics, the selected approach is the one provided by MatCalc since the available alternative, i.e., in-house developed kinetic models, are unable to describe the multi-component multi-phase systems of interest in this project with sufficient accuracy.

Concentrations of stabilizing elements, such as Ti, Nb and V up to 0.2% have been considered.

Three commercial thermodynamic models have been analyzed: ThermoCalc, MatCalc and JMatPro. They appear in substantial agreement in predicting the stability ranges of the possible phases and their fraction as a function of temperature, both for the reference Lo-Si and Hi-Si steels without microalloying and with Ti microalloying.

Titanium has been selected as the most promising microalloying element due to the low solubility of its carbides, nitrides, and sulfides. This permits to shift the precipitation ranges to higher temperatures with a lot of effects:

- Full removal of interstitials from the solid solution and at the same time of sulfur
- Formation of coarser precipitates due to the higher precipitation temperature leading to a lower inhibition contribution to grain growth during the final stages of industrial processing
- Reduction of the amount of austenite that forms during hot rolling of the Lo-Si variant, with impact on the development of crystallographic textures in the hot strip.

The simulations suggested that the use of 0.2% Ti is the best choice to produce a coarse and stable precipitation according to the aims of the compositional design of these steel grades.

The choice of Ti as a stabilizing element of the interstitials has been made not only because are the most stable than those Nb and V, with particles that tend to be coarser but also because it does not have a strong retarding effect on recrystallization kinetics unlike Nb. Furthermore, Ti stabilizes the ferrite phase and an addition of 0.2% can eliminate the partial transformation into austenite even in materials with 1% Si.

Casting and downstream transformation

Four different laboratory heats have been produced considering two nominal levels of Silicon (Low Si, High Si) and two levels of Titanium (Low Ti and High Ti). The synthetic data of chemical composition of materials are shown in Table 1. Figure 3 show details of treatments of the four laboratory ingots and codes used to identify the hot rolled samples.

Table 1 Chemical composition of the laboratory castings.

Campaign	Steel	C	Mn	Si	Ti	P	S	N	Al	Cu
Wave 1 (Reference)	LoTi-LoSi	0.0060	0.30	1.02	0.001	0.014	0.002	0.0047	0.51	0.015
	LoTi-HiSi	0.0060	0.30	2.92	0.001	0.014	0.002	0.0037	0.98	0.015
Wave 2 (Ti-Added)	HiTi-LoSi	0.0053	0.27	1.53	**0.200**	0.011	0.002	0.0032	0.51	0.015
	HiTi-HiSi	0.0061	0.32	2.97	**0.200**	0.012	0.002	0.0036	0.99	0.015

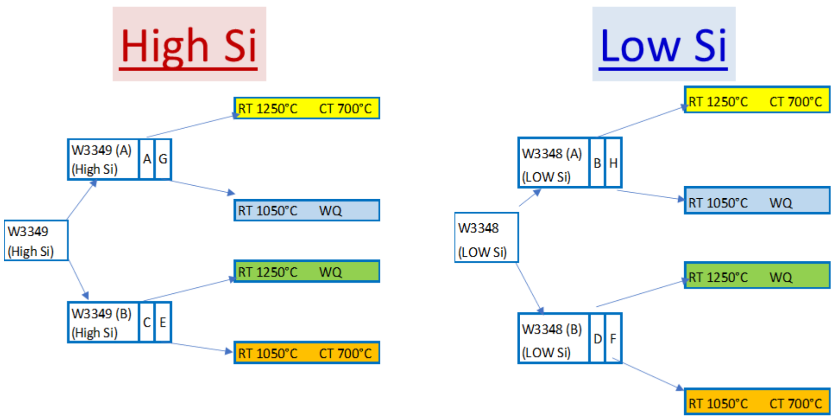

Figure 3 Schematic view of the hot rolling variants and codes used to identify the materials.

Figure 4 shows the processing conditions generated for hot band annealing from materials processing wave 1 (reference) and wave 2 (0.2% Ti-added).

- 2 chemical compositions; 1%Si (Low Si) and 3% Si (High Si)
- 2 reheating temperatures before hot rolling: high (1250°C) and low (1050ºC).
- 2 cooling strategies after hot rolling. Case "A" with coiling simulation at 700ºC, Case "B" with fast cooling (water quenching) to RT.

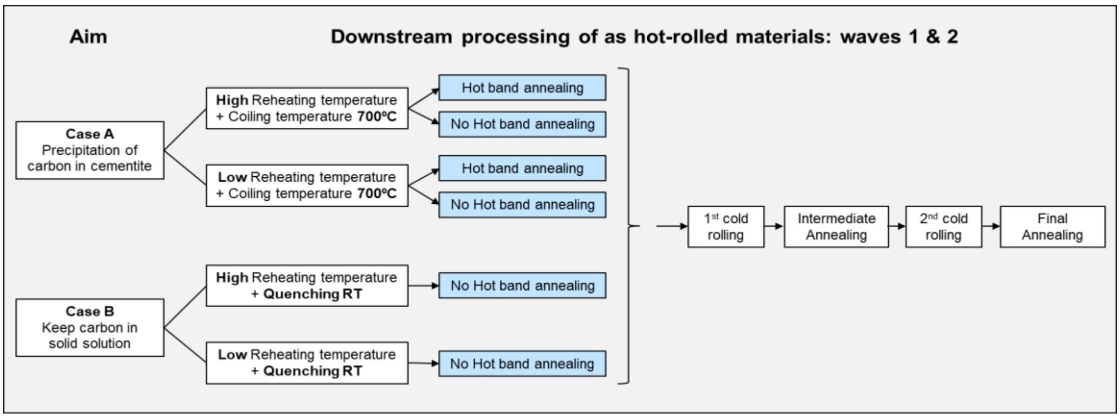

Figure 4 Conditions per chemical composition selected for subsequent downstream processing for material processing wave 1 and 2.

The variants of the upstream parameters were chosen to investigate multiple metallurgical effects:

a) the effect of chemical composition,

b) the impact on precipitation during processing,

c) the texture development.

All these effects can have an important impact on final magnetic properties. In the following sections the results obtained for the high Si variant (high and low Ti) will be illustrated in more detail due to the better performance in terms of core losses and more promising overall characteristics focusing EV/HEV traction motors.

Microstructure and Texture characterization

The Ti-added materials (Wave 2) after cold rolling and recrystallization annealing exhibited an average grain size slightly smaller than the Reference materials (Wave 1). This has been attributed to the presence of a volume fraction of precipitates between 150 and 200 nm whose size is greater by a factor of 5 to 10 compared to the reference material (Wave 1). However, no strong correlation has been observed between magnetic properties and grain size were observed.

As expected, the recrystallization textures of the Ti-added materials are generally less favorable than those of the reference steel because the reduced content of interstitials in the ferritic matrix during deformation increases the <111>//ND recrystallization components typical of ferrite [5]. In turn, this causes a reduction of the measured polarization that can be estimated in the order of 2-4%.

Precipitation characterization

Coarse precipitation on hot strips has been characterized by FEG-SEM determining the particle size distributions for the different phases. Finer precipitates in hot and cold rolled strips have been characterized by TEM/EDS from carbon extraction replicas. Typical size of the observed precipitates ranges from about 10 nm up to a maximum size of about 150-200 nm. Titanium radically modifies the state of fine precipitation observable at TEM: the precipitation in the reference materials (Wave 1) is made up of coarse AlN and fine (Mn,Cu)S, whereas in the 0.2% Ti variant (Wave 2) only carbosulfides ($Ti_4C_2S_2$) and carbonitrides Ti(C,N) were observed (See Figure 5).

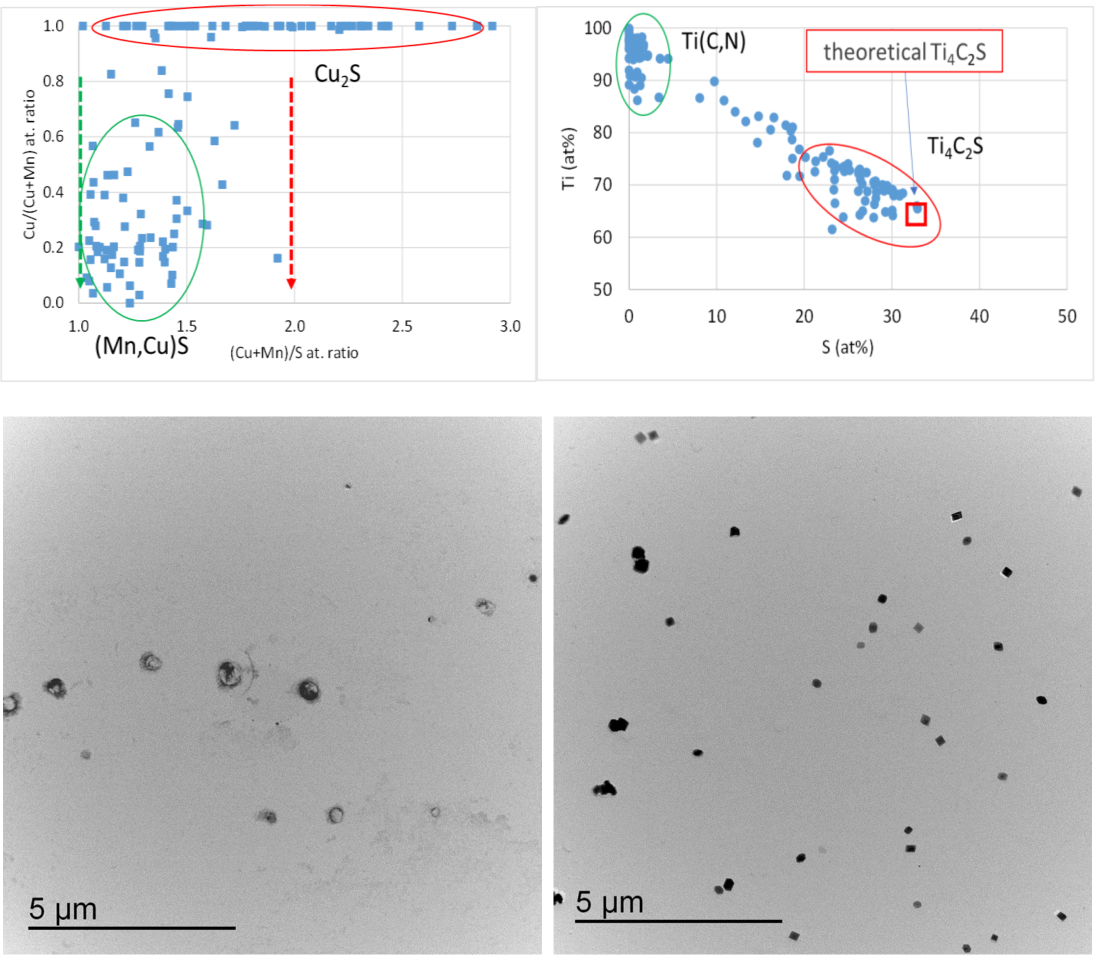

Figure 5: Typical precipitates observed at TEM and relative composition plots: a) (left side) Reference E (SRT=1050°C, no HBA); b) Ti-added G (SRT=1050°C, no HBA)

Magnetic and mechanical properties

The characterizations were carried out using Single Sheet Tester without applying any corrections with respect to Epstein frame measurements (Figure 6). 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 better. Slightly lower power losses at 400 Hz are associated with the lower reheating temperature (1050°C) and with the absence of HBA treatment. The polarization of Ti-added is found in average about 3-4% lower than the reference material. This can be explained by a less favorable texture due to the reduced amount of carbon in the ferritic matrix during deformation which increases the <111>//ND components.

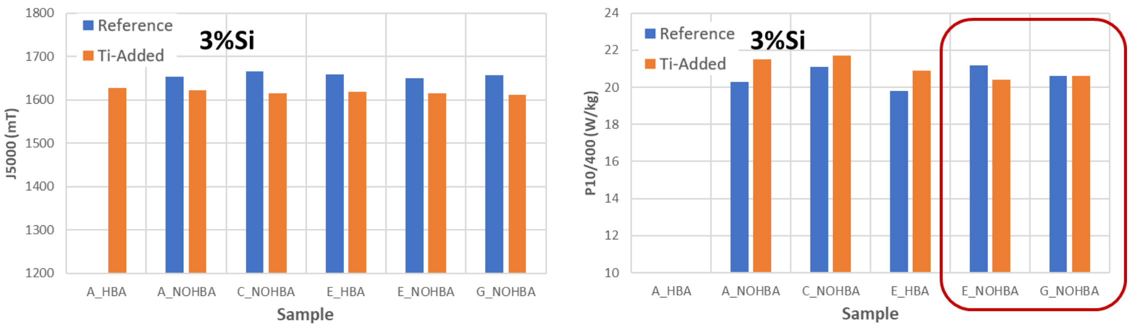

Figure 6 Core Losses P10/400 and Polarization J5000 measured on High Si materials in case of wave 1(Reference; 0.0010% Ti) and Wave 2 (Ti-Added; 0,2% Ti)

Additional features of the Ti-added steel

The presence of titanium is effective in eliminating the aging effect on core losses found in the low Si reference material, as shown in Figure 7.

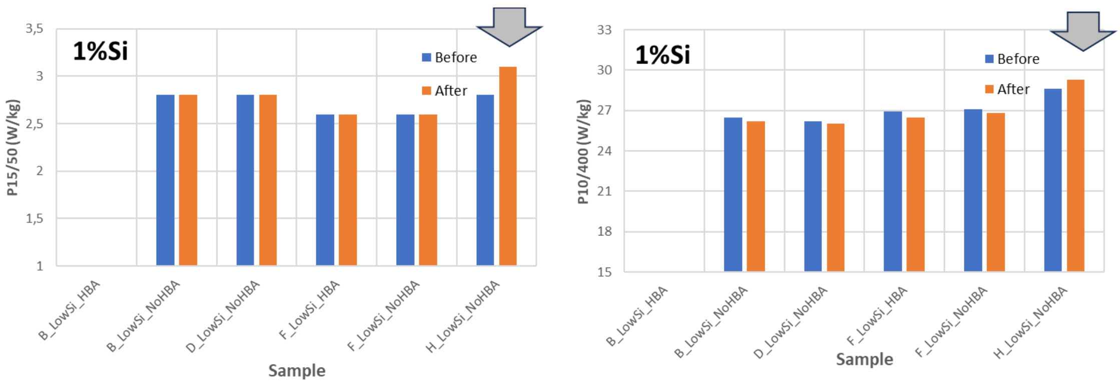

Figure 7 Magnetic aging observed in case of Low Si reference material – (Before Aging treatment; After aging at 225°C x 24h.

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 in Rp_{02} and about 36 MPa in Rm compared to the Reference material (Wave 1) it is about 22 MPa; the increase in UTS is about 36 MPa. Results are reported in Figure 8

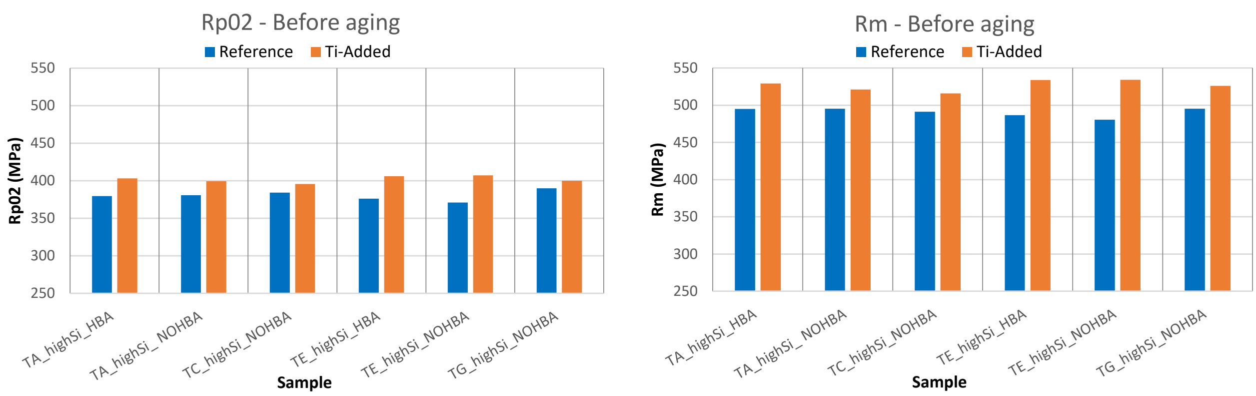

Figure 8 Yield Strength (Yield Pt.) and Ultimate Strength (UTS) observed on High Si materials in case of wave 1(Reference; 0.0010% Ti) and Wave 2 (Ti-Added; 0,2% Ti)

Work in Progress

From the processing viewpoint it is apparent that low slab reheating temperatures (1050°C) without hot band annealing permit to achieve an adequate low level of the power losses. Nevertheless, the first results suggest that there is room for further optimization of the performance of Ti- added steels. First of all, the amount of titanium can be increased (e.g. up to 0.5%) to further reduce the volume fraction of small precipitates affecting the grain growth kinetics. Then, a different distribution of the overall cold deformation between the two rolling stages could be of help in reducing the intensity of the <111>//ND recrystallization components, thus improving the polarization. An example of the optimized processing plan (Wave 3) is illustrated in Figure 9.

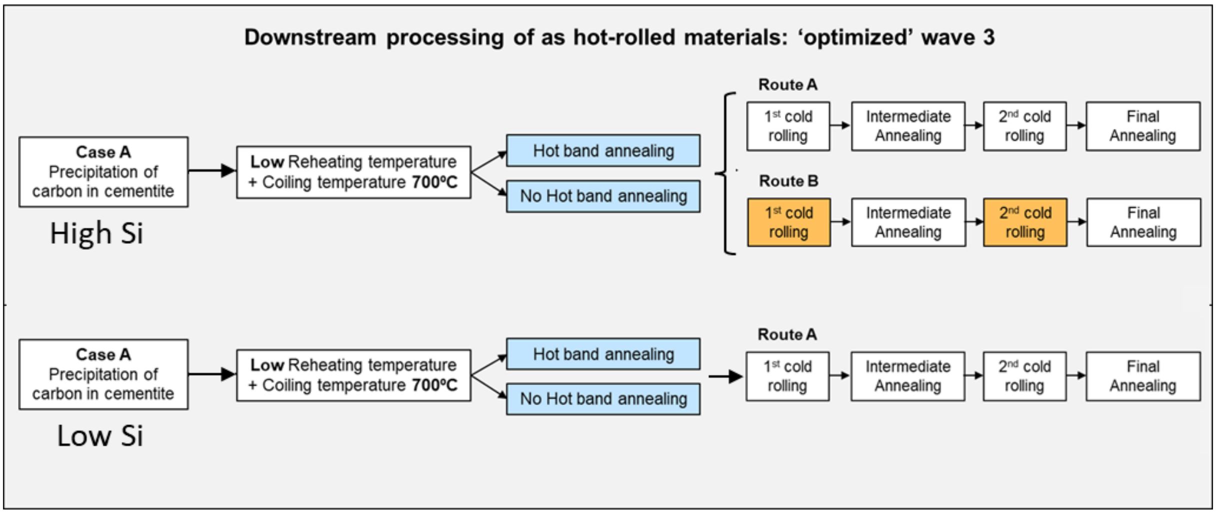

Figure 9: Conditions per chemical composition selected for subsequent downstream processing for the 'optimized' material processing wave 3.

References

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