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Extending the drive range of electric vehicles by higher efficiency and high power density traction motors, via a new generation of Electrical Steels

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Abstract

ArcelorMittal is a key supplier of electrical steels (ES) for challenging applications such as high power density automotive traction machines. Given the battery is the key restrictive power train element for battery electric vehicles, it is essential that the available battery energy is optimally used for a maximal drive range, so top efficiency electrical traction machines are essential. First of all they need to have an excellent performance over a wide frequency range. Next they need to have a high power density to add as little weight to the vehicle as possible, for a given mechanical output. And, last but not least, there is a need for reliability together with low production costs. These requirements translate in electrical steels optimised for different aspects: magnetic, electric, thermal and mechanical performance.

Our experience as ES provider for such machines has made us understand that the optimal electrical motor solution uses different ES for the rotor and for the stator: very low loss and high permeability grades for the stator and high strength grades for the rotor. ArcelorMittal therefore developed specific ES solutions for the rotors and stator resp. with a clear benefit in power density, efficiency and torque.

The use of optimised ES grades needs careful machine design, in order to maximise the potential of these ES. Therefore ArcelorMittal provides also a service of advanced magnetic and mechanical material characterisation not only at room temperature, but also at the exploitation temperature of the machine.

Keywords: Efficiency, electric drive, motor design, power density, power train

1 Introduction

Electric vehicles use electrical machines for traction and/or power generation. Very stringent demands are placed on these electrical machines. First of all they need to have an excellent performance over a wide frequency range to be able to perform optimally in each drive cycle. Next they need to have a high power density to minimise the weight and utilised volume in the vehicle, for a given mechanical output. And, last but not least, there is a need for reliability coupled with low production costs [1].

ArcelorMittal is an experienced supplier of electrical steels and has been involved in the development of optimum rotor and stator cores for these electrical machines. The specifications are more complex than for an average industry machine, given that the higher power density and robustness require ES optimised for different aspects: magnetic, electric, thermal and mechanical [6-9] performance.

2 Electrical steel choice

Fig. 1 shows the requirements on ES in hybrid vehicles using a permanent magnet synchronous machine (PMSM), which is the predominant machine used for this application. In the next paragraphs we will first discuss how to reduce the iron loss effect (§2.1), so improve the machine behaviour at high speeds and next (§2.2) how to increase the flux density, so improve the machine behaviour at low speeds. Furthermore for the high speeds in the rotor, the mechanical properties of the ES become a key design parameter (§2.3).

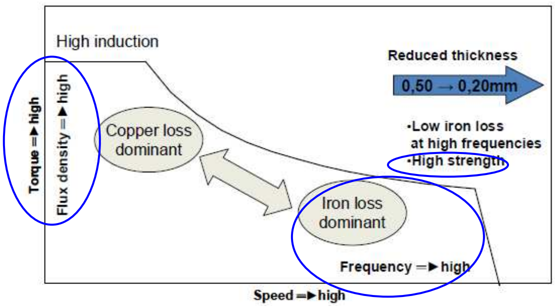


Figure 1: Impact of electrical steel choice for a hybrid application with PMSM [1]

2.1 Iron losses

The key performance aspect of electrical steels is to concentrate magnetic flux and a higher air gap flux results in higher torque output of a motor, current output of a generator or power transfer in a transformer. Unfortunately, the magnetisation processes taking place in the ES is nonlinear and dissipative. There is a certain amount of energy needed to realise the irreversible magnetisation processes, which leads to energy loss within the magnetic core. This energy dissipation is called iron losses and manifests itself as a warming up of the ES. The ratio between input and output power of an electrical machine is called the efficiency and it will be lower when higher losses occur. The total machine losses consist of friction losses, ventilation losses, copper losses, iron losses etc. Obviously, as an ES producer, ArcelorMittal can help to improve this efficiency by offering lower iron loss ES. Low loss grades can be realized by improving the structure and texture elements of the steel (hysteresis and excess part of the iron losses) as well as by working on the electrical resistivity (eddy current and excess part of the iron losses). The general way to increase the resistivity is by alloying mainly with Si. Eddy current losses can also easily be reduced by working with thinner gauges, because these thinner gauges enable the eddy current losses to be reduced, without having to further increase the alloying content, since the latter implies a loss of saturation polarisation and thermal conductivity (check §2.4). As a consequence for automotive traction, the use of thinner than the classical 0,35mm grades, is a straightforward evolution.

Coming back to the PMSM, the fact that the rotor of this machine runs at a speed synchronous to the stator field, implies that most of the iron losses will occur in the stator. It therefore is key that the ES used in the stator is designed for low iron losses and this in particular at high frequencies. ArcelorMittal therefore went beyond the EN10106 [5] or IEC 60404-8-4 classification of losses at 50Hz. We saw the need of a classification at a higher frequency, and chose 400Hz for our new thin low loss grade guarantees. 400Hz certainly does not fully represent the actual frequencies in the machine, but it already gives a clear view on the higher frequency behaviour of the steel.

ArcelorMittal calls its low loss steel range “Save” since the reduction of losses they represent allow to save energy, and also to save on material volume because “Save” grades allow to make more compact machines. A typical example is the “Save 30-15” a grade in 0,3mm gauge with losses at 1T and 400Hz below 15 W/kg.

2.2 Polarisation and permeability

The basic principle of electrical machines is obviously the flux transfer between the rotor and stator in a rotating machine, and between the primary and secondary winding in a static machine. If the core material used for the motor, generator or transformer allows for an easier magnetisation process, there will be less magnetising current needed to achieve a certain torque output or energy transfer. It is therefore critical to have ES with high polarisation and high permeability. An example is shown in Fig. 2. The reference of this graph is the M330-35A and M330P-35A grades, which are often used for automotive applications. The 4 grades shown have the same loss level at 50Hz, but quite different magnetisation curves. It is clearly visible that in order to reach the same polarisation level, for a certain air-gap flux, the high permeability grades require less magnetisation current to achieve the target.

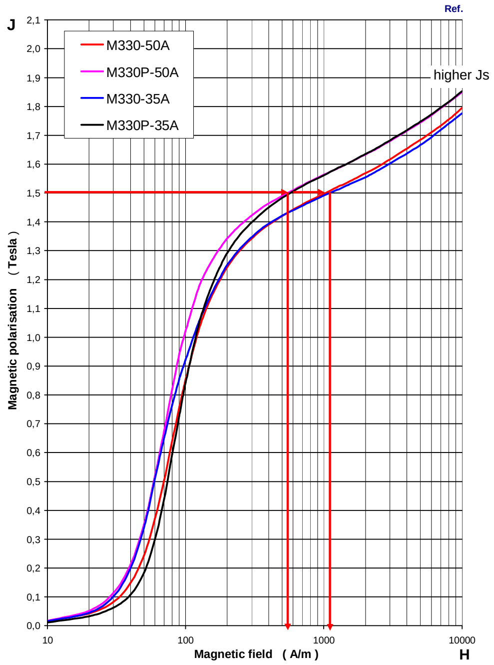


Figure 2: Impact of polarisation on air-gap flux generation potential of the electrical steel

ArcelorMittal developed a specific product range which is capable of assuring a better air gap flux, hence torque generation, specifically designed to combine high permeability for the torque with low loss as described in the paragraph above. An example of such a grade is the “Torque 30-19” a grade with a gauge of 0,30mm, guaranteed low losses below 19 W/kg at 1T and 400Hz and on top of that a high polarisation level at 5000 A/m of min. 1,66T.

2.3 Mechanical strength

Increasing the speed of the rotor allows to make more compact machines, for a given power output. This brings a clear focus on having high yield strength levels for the rotors of PMSMs, so they better can withstand the mechanical solicitation linked to the permanent magnets housing, the electromagnetic and centrifugal forces.

In electrical steels magnetic and mechanical properties are intertwined. Fig. 3 shows general tendencies on how polarisation (saturation polarisation in this graph) and mechanical properties (in this example tensile strength) evolve with loss levels, for standard fully processed non-oriented ES.

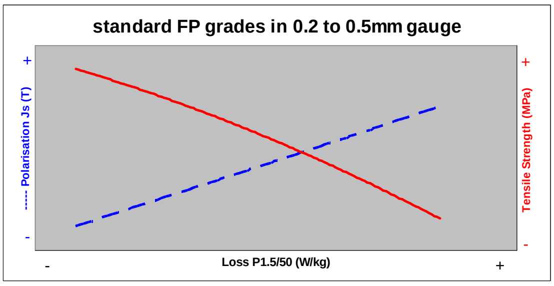


Figure 3: Evolution of saturation polarisation (Js) and tensile strength with loss reduction in standard electrical steel production

Also, it can be seen in Fig. 4 that low loss and high permeability is intrinsically difficult to realise. It must therefore become clear that the ideal ES with a high strength level for high speed rotors and a low loss and high permeability for magnetically optimised stators is a challenge to reach.

For the machine designs that allow using a different grade for the rotor and stator, ArcelorMittal developed a specific ES range with high yield strength, which combine good high frequency losses with a high level of mechanical properties. The “Speed 35-440” and “Speed 35-510” have a gauge of 0,35mm and resp. guaranteed yield strength of 440 and 510 MPa. The guaranteed loss levels at 1T and 400Hz are resp. 23 and 28 W/kg, which is a good level for rotor applications.

2.4 Thermal conductivity

Clearly, a certain amount of iron loss is unavoidable. This heat needs to be evacuated to a maximum extent out of the machine: either in a radial direction towards the stator housing, or axially. To achieve this in an optimum way, it is important to have ES steels that allow easy evacuation of the heat throughout the lamination stack, hence with a high thermal conductivity. The thermal conductivity of electrical steels depends on their chemical composition (fig. 4) and is therefore strongly linked to their electrical resistivity, dynamic iron losses and saturation polarisation. Higher alloying contents do allow reducing the losses, but unfortunately, they reduce the thermal conductivity as well.

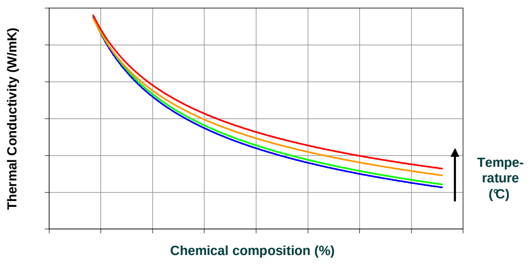


Figure 4: As the alloying content increase towards the right hand side, the thermal conductivity is reduced. Furthermore, thermal conductivity increases with increasing operating temperature.

2.5 Electrical steel selection for automotive traction

The predominant machine type used in automotive traction is a PMSM. Fig. 5 summarises the key ES choice parameters.

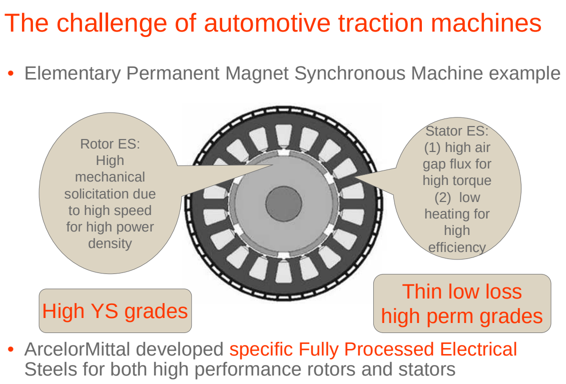


Figure 5: Layout sketch of a generic permanent magnet synchronous machine and electrical steel grades specifications for both rotor and stator

3 Improved modelling of iron losses in machines

A sufficiently accurate estimation of iron losses occurring in the machine's stator/rotor parts is indispensable to effectively carry out the electromagnetic and thermal design of electric machines.

Iron losses in ferromagnetic materials are usually measured and theoretically described under well-defined, standardised conditions like e.g. the Epstein frame test, carried out under uni-directional and sinusoidal magnetic induction. Also standardised material sample dimensions are used, resulting in the specific iron losses (in W/kg) of a particular ES grade for a given magnetic induction value and frequency value. To give an example: for a M235-35A grade of 0.35mm gauge, the specific iron loss at 1.5T and 50Hz is less than 2.35 W/kg.

However in rotating electrical machines, the occurring magnetic flux paths, flux waveforms, steel part geometries, lamination manufacturing techniques and mechanical constraints are far more complex than in case of the lab conditions of the Epstein measurements. Hence the actual iron core losses (in W) dissipated in electrical machines cannot be related in a simple way to the Epstein loss data (unfortunately, it is far from straight-forward like simply multiplying the specific loss value with the mass of the ES parts).
To be more specific, compared to the standardised iron loss measurements there are a lot of additional factors influencing the iron losses in machines:

- the magnetic flux wave forms are not simply sinusoidal and unidirectional, but contain higher harmonics in time (due to saturation effects, stator slots, power electronics such as PWM, skin effect);
- the magnetic fields can become, in some regions of the machine, vector properties (known as rotational magnetisation). These non-unidirectional magnetisation conditions give rise to rotational losses;
- in some regions of the machines, elevated magnetic induction levels occur;
- especially for electrical machines utilised in electric vehicles, the machine operates at different elevated operating frequencies

In this section 3 we will show how we tackle the issue of improving the estimation of the iron losses by numerical methods, by taking into account the above-mentioned aspects.

Moreover, also building stresses (compression applied to the steel lamination when fitting it into the machine housing) [10], lamination punching [3, 10-13] and elevated operational temperatures affect the magnetisation processes in the machines and the resulting machine's iron losses. In order to predict the iron losses more accurately, these effects should be considered as well, and incorporated to some extent in the envisaged improved iron loss models. In the next section 4 we will show some of the advanced characterisation results of the effect of temperature, on the iron losses and the magnetisation curve (or permeability).

In the next paragraphs the current state of the art of the improved iron loss modelling is highlighted: in the framework of a collaboration between ArcelorMittal (R&D Gent) and the IEM (Institute of Electrical Machines of the RWTH Aachen), numerical methods were developed [2-3] to improve – in relatively wide operational ranges of magnetic polarisation[1] *J* and frequency *f* – the estimation of iron losses occurring in rotating electrical machines.

This improved iron loss model can be seen as a further elaborated Bertotti-based loss-separation model [4]. To recapitulate, the well-known classical iron loss model of Bertotti describes nicely the three different iron loss components under unidirectional and sinusoidal magnetic flux density: the (quasi-)static hysteresis losses, the dynamic classical Foucault losses (also known as eddy current losses), and the dynamic excess losses:

$$P_{Fe}(J_p, f) = k_{hyst} J_p^2 f + k_{eddy} J_p^2 f^2 + k_{exc} J_p^{1.5} f^{1.5} \qquad (1)$$

In the following, we also use a variant of equation (1) which is suitable for a wider range of magnetic polarisation values:

$$P_{Fe}(J_p, f) = s_{hyst} J_p^{(\alpha+\beta J_p)} f + s_{eddy} J_p^2 f^2 + s_{exc} J_p^{1.5} f^{1.5} \qquad (2)$$

In both equations, the eddy current parameter can be computed based on the value for thickness, electrical conductivity and mass density [4]. The other parameters are obtained by fitting the measurement data (as a function of peak magnetic induction J_p and frequency *f*).

Nevertheless, Bertotti's original approach does not take into account rotational losses and higher harmonics, so estimated loss values are expected to be smaller than the losses occurring in reality. These limitations underline the need to extend the loss model by describing also these mentioned effects which additionally contribute to the iron losses.

The ArcelorMittal improved iron loss model on the other hand includes the most relevant additional aspects which influence (mainly deteriorate) the actual iron losses occurring in rotating machines:

- elevated magnetic induction levels
- higher harmonics in time and space
- nonlinear magnetisation effects
- spatial vector fields; rotational magnetisation
- elevated operating frequencies

ArcelorMittal's state-of-the-art iron loss description reads as follows:

$$P(J, f) = s_1\left(1 + (r(J_{\max}) - 1)\cdot c\right) J_{\max}{}^2 f + s_2 \sum_{n=1}^{\infty} J_n{}^2 (nf)^2 + s_3 \sum_{n=1}^{\infty} J_n{}^{1.5} (nf)^{1.5} + s_4 J_{\max}{}^{s_5} \cdot f^2 \qquad (3),$$

taking into account the following definitions:

- s_i : all five parameters are fitted material parameters (depending on the ES grade)
- $J_{\max}$: amplitude of the ground (first) harmonic component of the flux density [T]
- J_n : amplitude of the *n*-th harmonic component of the flux density, with $J_n{}^2 = (J_{nx}{}^2 + J_{ny}{}^2)$
- f : fundamental frequency, in Hertz [Hz]
- c : flux distortion factor, $c = J_{\min} / J_{\max}$
- $J_{\min}$: minimum value of flux density amplitude, evaluated over one electrical period [T]
- r : rotational loss factor (empirically determined)

Equation (3) and (2) are extensions on the physically based loss model of Bertotti. Equation (3) is rather a mathematical iron loss description, which results in a good fit between measurements and calculations. Therefore is it a valuable mathematical tool for the estimation of iron losses in electrical machines. However, a further elaborated model based on equation (2) tends to be better suited when attempting to link more physical and micro structural features (such as temperature, see section 4) to the iron loss description:

[1] Note: for application related data we typically use the property magnetic flux density or magnetic induction *B*, whereas for material related data we specify the magnetic polarization *J*. Definition: $B = J + \mu_0 H$, with μ_0 the permeability of vacuum (air) and *H* the magnetic field.

$$P(J,f) = s_{hyst}\left(1+(r(J_{\max})-1)\cdot c\right)J_{\max}^{\ (\alpha+\beta J_p)} f \\ +\ s_{eddy}\sum_{n=1}^{\infty} J_n^{\ 2}(nf)^2 \ +\ s_{exc}\sum_{n=1}^{\infty} J_n^{\ 1.5}(nf)^{1.5} \qquad (4)$$

Most definitions are similar as in equation (3), only the material parameters are different:

- s_{eddy} : is calculated from electrical conductivity, thickness and mass density [4]
- s_{hyst} , s_{exc} , α and β are fitted material parameters (depending on the ES grade)

The proposed calculation method for the improved estimation of iron losses in electrical machines is shown in fig. 6. The general framework is valid for both iron loss description variants (equations 3 or 4). The method consists of using the specific loss *W(J,f)* characteristics obtained by standardised Epstein frame measurements, in order to fit the material parameters of the improved iron loss description (equation 3 or 4). As been said, this iron loss description accounts for the presence of the real life conditions occurring in electrical machines such as – in some regions of the ES – elevated magnetic induction levels, waveforms with higher harmonics and rotational magnetisation patterns.

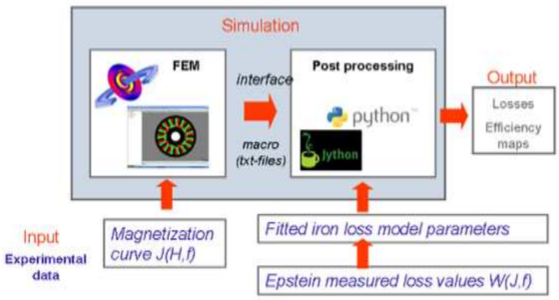


Fig.6: General overview of the numerical scheme of the ArcelorMittal iron loss modelling approach.

On the other hand, the magnetisation curves *J(H,f)* also obtained by the standard Epstein measurements serve as input for the 2D finite element computations of the electrical machine under evaluation, identifying the local flux densities for each time step during one electrical period. For one particular working point of the machine, the magnetic induction values in every finite element of the machine's stator lamination are retrieved, and this is repeated at different time instants during one electrical period.

These magnetic induction values (as function of time and finite element index) then serve as input for the post-processing tool – implemented into the numerical environment at ArcelorMittal Research Gent, which can run independently from the FEM calculations – to calculate the iron losses according to the ArcelorMittal iron loss model of equation 2. This method is partly validated with higher harmonic measurements, resulting in good accuracy and reliability.

These calculations can then be repeated for different operational points – as a function of torque (current) and speed (frequency) – and all such results can be combined in so-called efficiency maps. Using these efficiency maps the influence of different ES grades on the performance of rotating electrical machines can be studied.

In a next step, also a particular drive cycle – within which the electrical machine is operating – could be taken into account as input, to result in an overall iron loss or efficiency evaluation of the specific combination of machine, ES grade and drive cycle, see fig. 7.

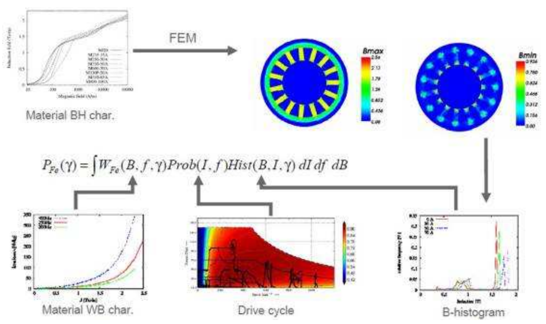


Fig 7: Methodology of iron loss estimation with ArcelorMittal input, B(H) curves and loss P(B), taking into account a particular drive cycle.

Furthermore, it's important to stress that we focus on the iron losses occurring in rotating electrical machines; the conductor (Joule) losses can be calculated easily in parallel with the iron losses; the calculation of the losses dissipated in the permanent magnets (if there are any) is not included here.

4 Influence of elevated temperature on electromagnetic properties

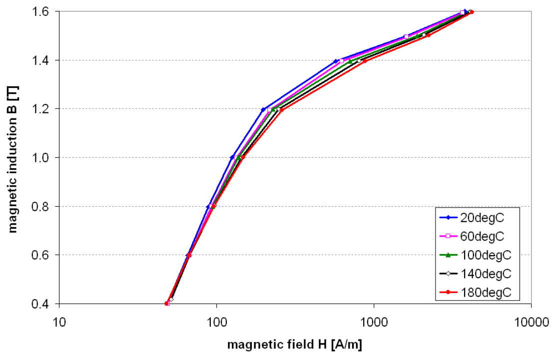
Magnetic material data available from suppliers is in most cases measured at room temperature. However, given the heat dissipation during the operation of the electrical machine, the ES core can be operating in a temperature range significantly above room temperature. The following results allow the reader to assess the effect of elevated temperature on the electromagnetic properties of high alloyed fully processed non-oriented ES.

Firstly, electrical conductivity is measured for different temperature set points, utilising a 4-point DC-resistance measurement method on a strip of 60mm wide and 300mm width. The measurement setup is placed in a furnace and measurements are performed at temperatures between room temperature and 180°C. Within this range, the electrical conductivity decreases linearly with increasing temperature; it is known that the slope in (S/m)/°C is more or less the same for different fully processed ES. Hence, for high alloyed ES having a high room temperature value of electrical conductivity, the relative change of conductivity between 20°C and 180°C is only -11%, whereas for lower alloyed electrical steels with lower room temperature value of electrical conductivity, the relative change within the same temperature range can be up to -30%.

Secondly, magnetic measurements are performed on a stacked core of ring shaped laminations cut by spark erosion (inner and outer diameter: 86 and 100 mm respectively) of the same high alloyed ES grade. A thermocouple is welded on one of the ring laminations (inside the excitation and measurement windings) in order to precisely control the temperature of the ring core when placed in the furnace. Magnetic measurements are performed for different B values and different excitation frequencies, from 2 Hz to 1 kHz.

4.1 Influence of temperature on the magnetisation curve

In figure 8 the effect of temperature on the low frequency (2 Hz) magnetisation curve is shown, as well as the effect on the amplitude permeability ($\mu_{rp}(B_p) = B_p/\mu_0 H_p$), which is actually a different representation of the same data. There is a slight influence of the temperature between 0.6T and 1.6T: the high temperature magnetisation curve is inferior compared to the room temperature one. In other words within this induction range the high temperature permeability is lower than the room temperature one.



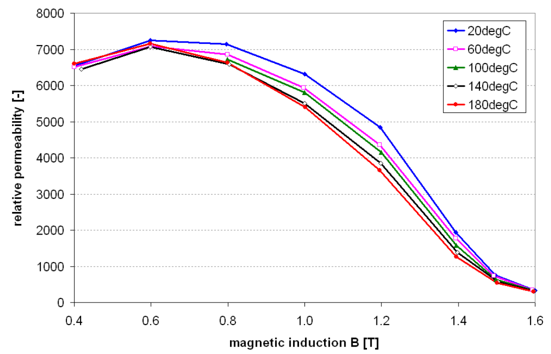


Fig 8: Effect of temperature on the magnetisation curve and on the permeability

4.2 Influence of temperature on the iron losses

In general, the total iron losses (at a certain frequency and magnetic induction level) decrease when the temperature goes up, see Fig. 9. This is mainly because the electrical resistivity increases when the temperature increases, hence the eddy current losses and the excess losses both decrease with temperature.

In Fig. 10 magnetisation loops are shown for the two extreme cases of temperature (20°C and 180°C), for equal peak induction level (1.5T) and the two extreme frequencies (2Hz and 1kHz). The decrease in permeability with increasing temperature as shown in Fig. 8 is of course also visible in the change of hysteresis loops when comparing high temperature with low temperature curves. When comparing 180°C with 20°C, the relative decrease in coercivity at 1 kHz is 10% (257A/m at 20°C; 230A/m at 180°C). Notice that also for the magnetization loops at 2 Hz, this relative decrease is approximately the same (40A/m at 20°C; 36A/m at 180°C), although the relative contribution of the dynamic losses compared to the static hysteresis losses is much lower than at 1kHz, which is a first indication that the difference in iron losses cannot be explained by decrease of electrical conductivity only, but that there's also an effect on the static hysteresis loss part.

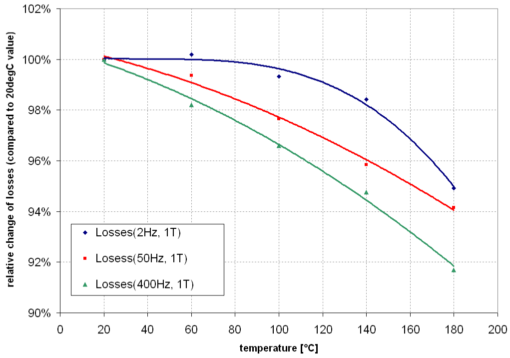


Fig 9: Relative change as a function of temperature of the total measured iron losses at 1T and three different frequencies, when compared to the values at room temperature.

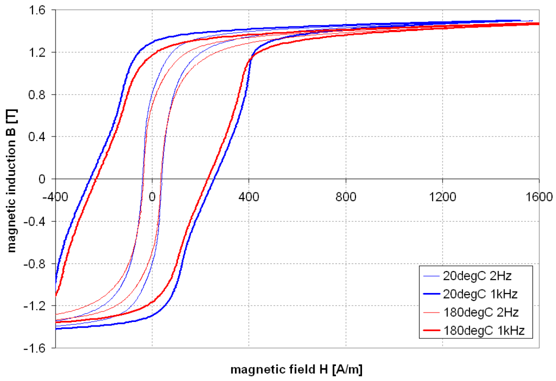


Fig 10: Magnetization loops for B_p = 1.5T: comparison of high vs. low temperature and high vs. low frequency.

4.3 Temperature dependence of the ArcelorMittal iron loss model coefficients

In order to quantify the different effects, an iron loss separation is performed based on equation (2), being the Bertotti model with modified power of B (power not equal to 2, but depending linearly on B). Fig. 11 shows the temperature dependence of the five material parameters. Remember that $s_{eddy}(T)$ is computed starting from the electrical conductivity $\sigma(T)$, which is measured by the 4-point resistance method. The other 4 parameters are fitted against measurements. Both α and β are sensitive to temperature and reflect the change of the magnetisation curve with temperature as discussed in section 4.1. Fig. 12 zooms in on the other three parameters, and also gives the relative change of electrical conductivity and its square root. According to [4], the excess losses can be approximated as proportional to the square root of σ. Based on the iron loss separation, it becomes clear that not only the dynamic loss components, but also the static hysteretic one decreases with increasing temperature, as anticipated in section 4.2.

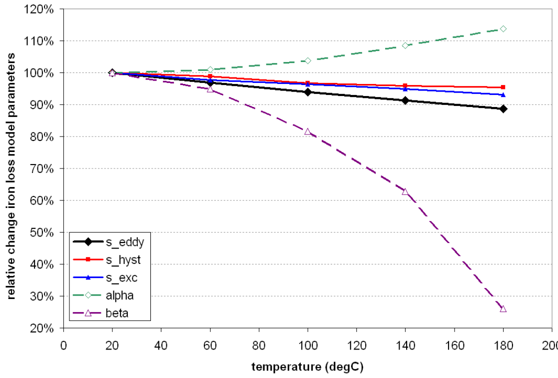


Fig 11: Temperature dependence of the relative change of the five parameters of the iron loss description as equation 2, compared to the room temperature ones.

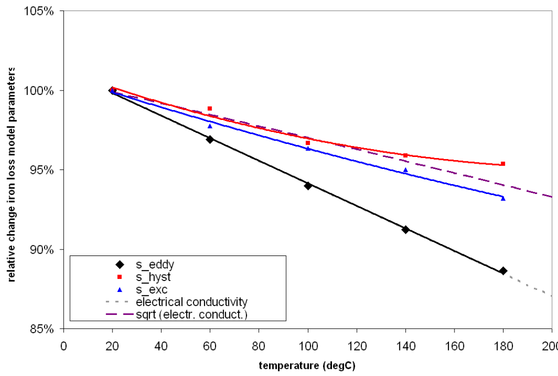


Fig 12: Temperature dependence of the relative change of a subset of the parameters of the iron loss description as equation 2, compared to the relative change of the electrical conductivity and its square root.

5 Conclusion

ArcelorMittal, as electrical steel producer, is offering to help the electrical traction machine designer to meet the tough challenge of defining

maximal power density output electrical machines. We first of all developed specific ES steel grades: (1) magnetically very soft types for the stator: “Save” for compact high efficiency and “Torque” for machines with high mechanical output and (2) mechanically very hard types for the rotor called “Speed”. This paper shows the different elements that define the optimal electrical steel choice: iron losses, permeability, thermal conductivity and mechanical strength. We wish to assist our customers further, by also providing the design engineers advanced magnetic and mechanical technical data to make the machine design calculations more precise. Furthermore we have developed our own iron loss calculation tools to better estimate the iron losses of our grades when built into e-machines. We focused in this paper specifically to provide magnetic data at the exploitation temperatures of the electrical steel in the machine. We obviously find – for specific ES grades used in automotive traction – the well known temperature effect on the eddy current and excess losses, via the electrical resistivity effect. Additionally, the hysteresis behaviour of the material is also affected by the machine exploitation temperature: both coercive field and permeability are affected. The latter effect is not taken into account in commercial modelling tools for e-machine field and iron loss calculations. The ArcelorMittal loss model does propose a way to implement such effects in a more precise post processing solution.
In this way we aim, not only contribute to the extension of the drive range (km) of electric vehicles, but also, to allow the power train specialist to make optimal material choices, which allows them to define their machine in a most cost effective way.

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