Temperature-dependent modelling of magnetic ageing of FeSi electrical steels

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A B S T R A C T

This paper deals with the temperature-dependent modelling of iron losses in the context of magnetic ageing of electricals steel used in high power electrical machines. First, two electrical steel sheet grades were heat treated at three temperatures in order to study the ageing effect evolution as a function of temperature. Results show a significant increase in iron losses for both steel grades. Then, considering the link between the macroscopic magnetic properties evolution (effect) and the microscopic precipitation (cause), the Johnson – Mehl – Avrami – Kolmogorov (JMAK) law describing the kinetics of precipitation was applied to model the time evolution of magnetic ageing. By coupling this model with the Arrhenius' law, a model is developed to be able to predict the ageing for several temperature levels.

1. Introduction

The ageing effect is the consequence of irreversible processes in the material, which usually correspond to the formation of precipitates at the material microstructural scale. Magnetic ageing can be triggered right from the manufacturing process of electrical machines (if heat treatments are carried out) or later in-use depending on the operating temperature of the machine. This phenomenon influences the magnetic material usage properties at the macroscopic scale and consequently may significantly impact the electrical machine performances, especially in terms of energy efficiency.

In the literature, various experimental studies have been carried out to help understanding the impact of magnetic ageing on magnetic properties [1–3]. However, these works have been rarely interested in modelling the time–temperature effect on the magnetic properties. Indeed, the influence of magnetic ageing on magnetic properties depends on several parameters related to the precipitates (volume fraction, size, distribution, …) [1–3]. According to Néel's theory [4], in the first order, the evolution of the coercive field is directly related to the volume fraction of the precipitates. In [5], a model based on the Johnson – Mehl – Avrami – Kolmogorov (JMAK) law describing the kinetics of precipitation, which is directly linked to the volume fraction of precipitates, has been proposed to account for the effect of ageing on the losses under isothermal conditions. As the coercive field is linked to the iron losses [6], the JMAK model was employed to directly represent the magnetic ageing, in terms of iron losses, in direct link with the volume fraction of precipitates.

However, in the electrical machines the temperature is usually inhomogeneous and varies with the manufacturing processes and the operating conditions. Indeed, during the manufacturing processes of high-power electrical machines, electrical steels can be subjected to temperatures above 160 °C over periods of dozens of hours (impregnation process and shrink-fitting for instance). Even smaller-sized electrical machines can be subjected to significant temperatures whether in the context of automotive, up to 150 °C for traction motors [7] and up to 180 °C for claw pole alternators [8], or in severe operating condition environments such as in aerospace turbines where temperatures of about 350 °C and above are observed [9].

Consequently, the model should be applicable for temperatures in industrial operating conditions along with the consideration of temperature variations during operation. Therefore, in this paper, we propose to extend the ability of the model introduced in [5] to predict, with a temperature-dependent model, the ageing effect for several temperature levels.

The modelling approach presented in [5] allows to model the magnetic ageing for a given temperature after having carried out the ageing measurements. However, it is not a temperature-dependent model as it does not explicitly depend on the temperature and the obtained parameters are valid only for the considered temperature. The objective of this paper is therefore, from a limited number of isothermal ageing

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measurements at different temperatures, to combine the JMAK model with the Arrhenius' law in order to propose a temperature-dependent model allowing to model the ageing effect over a defined range of temperatures. This model would be directly applicable, as a first approach, for non-isothermal temperature profiles observed in some manufacturing processes or operating conditions of electrical machines.

First, the experimental protocol to assess the magnetic ageing of two electrical steel grades at three temperatures is presented. Then, the experimental results are summarized in terms of magnetization and iron losses for the considered ageing temperatures. Finally, after presenting the JMAK model with the inclusion of the Arrhenius' law to account for the temperature-dependent model, this one is applied to the studied electrical steel grades. The results are finally discussed along with the limitations of the proposed model.

2. Experimental methodology

This work was carried out on two FeSi (Si-3 %) electrical steel grades with 0.65 mm nominal thickness, M400-65A and M600-65A, which are commonly used in magnetic cores of high-power electrical machines, especially for large alternators. The samples are cut by Wire Electrical Discharge Machining (WEDM) to limit the cutting effect on magnetic properties. The final dimensions are 300 mm × 20 mm × 0.65 mm. Moreover, they were not coated and all the measurements were performed in the rolling direction.

The experimental protocol, similar to the one presented in [5], is illustrated in Fig. 1. For each ageing temperature, the sample is subjected to a heat treatment cycle consisting of multiples heating steps regularly interrupted by an air-cooling step to carry out the magnetic characterization at room temperature. Each heating step has a duration varying between 3 h and 15 h depending on the ageing temperature (the higher the temperature, the shorter this duration is). Since the phases of temperature change (ascent, descent) are significantly shorter than the heating time, Fig. 1, the hypothesis is made that these have no influence on magnetic ageing.

Three ageing temperatures are considered: 160 °C, 180 °C and 200 °C for total ageing times ranging from a hundred hours to more than two hundred hours. As the JMAK model is based on the first-order Néel's theory [4] which assumes that there is no change in the phase of formation of precipitates, the three studied temperatures are close enough to limit this risk of phase change while considering representative temperatures of the industrial context. According to the framework of the study, the choice is made to carry out magnetic measurements rather than an exhaustive study of the nature of the precipitates.

The magnetic measurements are performed with a Single Sheet Tester, associated to the MPG200D equipment from Brockhaus Measurements, in accordance with the standard IEC 60404–3. The normal magnetization curves and the iron losses were measured at 50 Hz under sinusoidal magnetic flux density for peak values varying from 0.1 to 1.6 T.

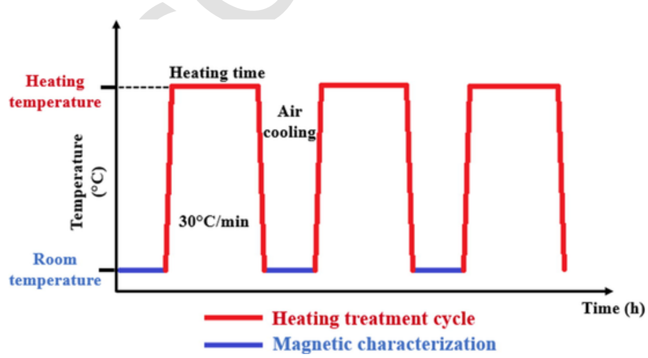

Fig.1. Experimental protocol.

The quantification of the ageing effect on both magnetic characteristics is determined as a relative evolution (also called ageing index) to the reference (non-aged) properties. This relative evolution is calculated with $\Delta P/P0(\%)$ for the iron losses and with $\Delta H/H0(\%)$ for the magnetic field required to reach a given magnetic flux density. $P0$ (resp. $H0$) represents the reference iron losses (resp. magnetic field) measured before heat treatment and ΔP (resp. ΔH) the difference between the iron losses P (resp. magnetic field H) at a given ageing time and the reference value $P0$ (resp. $H0$).

In the following, for the sake of synthesis, the analysis of magnetic properties evolution with ageing is presented for 1.5 T. Besides, this magnetic flux density level corresponds more or less to the practical operating point in the magnetic core of electrical machines. However, even if the final ageing index varies as a function of the magnetic flux density, we observe that the ageing kinetics remains similar.

3. Experimental results

For both grades, and each ageing temperature, the experimental results are given for the magnetic field ageing index in Fig. 2 and Fig. 3, and for the iron loss ageing index in Fig. 4 and Fig. 5.

First, we can see that the ageing impacts significantly the magnetic field H required to reach 1.5 T (although we are close to magnetic saturation). This field increases with time as well as with the ageing temperature. Even if both studied electrical steel grades show significant ageing indexes, the M400-65A sample (see Fig. 3) is more impacted by the heat treatment than the M600-65A sample (see Fig. 2). Conclusions about iron losses are similar and more significant as we can see in Fig. 4 and Fig. 5. Additionally, the following points should be emphasized.

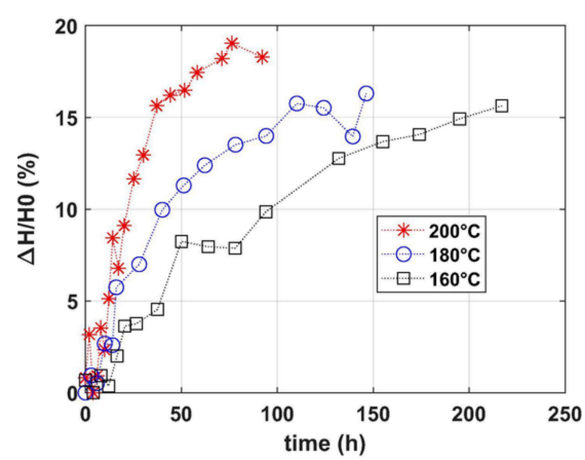

Fig. 2. Relative magnetic field evolution- M600-65A, B = 1.5 T, 50 Hz – H0 = 504 A/m.

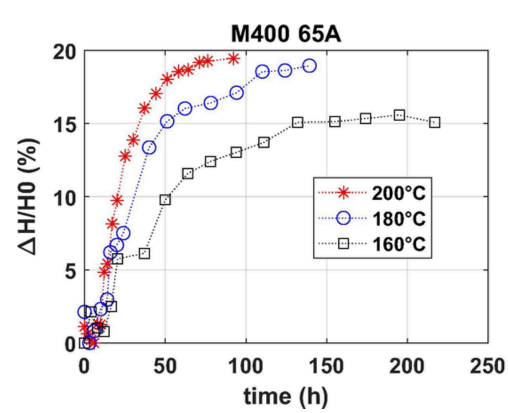

Fig. 3. Relative magnetic field evolution- M400-65A, B = 1.5 T, 50 Hz – H0 = 580 A/m.

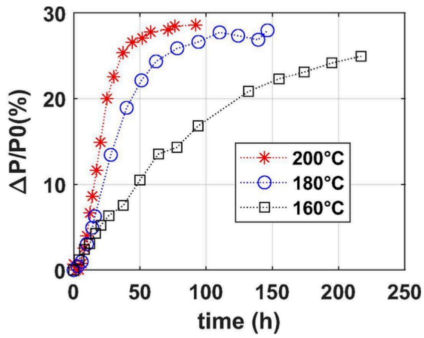

Fig. 4. Relative iron losses evolution- M600-65A, B = 1.5 T, 50 Hz – P0 = 5.00 W/kg.

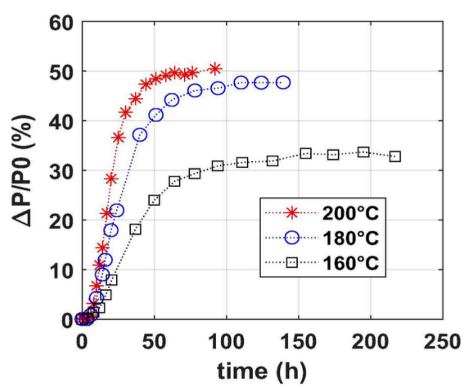

Fig. 5. Relative iron losses evolution- M400-65A, B = 1.5 T, 50 Hz – P0 = 3.26 W/kg.

First, the evolution of H at B = 1.5 T and the corresponding iron losses are qualitatively both evolving with the same kinetics. This evolution, Fig. 2, is usually reported for the iron losses but rarely mentioned in the case of the magnetic field. In addition, especially for the M400-65A grade, Fig. 3 and Fig. 5, the magnetic field and iron loss evolutions at 160 °C do not seem to have the same asymptotic value as for the temperatures at 200 °C and 180 °C. This was already observed by Ray *et al.* [10] who attributed this effect to less stable precipitates forming at low temperatures. These metastable precipitates may evolve after a longer heating time into stable precipitates, leading to a second increase of the ageing index. The iron loss asymptotic level will be then comparable to the one obtained with higher temperatures. Finally, at 1.5 T – 50 Hz, the ratio between the iron losses of the M400-65A and the M600-65A grades before ageing treatment is of 0.65. At the end of the ageing treatment at 200 °C (asymptote reached), this ratio increases approximately to 0.75. Therefore, it is not constant with the heating treatment and this seems to indicate that the grade M400-65A is more sensitive to ageing, which is consistent with the observed results.

From the results on iron losses, the objective is now to model their evolution as a function of time and temperature.

4. Modelling of magnetic ageing

4.1. JMAK model

The JMAK (Johnson-Mehl-Avrami-Kolgomorov) model is a phenomenological model widely used to describe the kinetics of different physical phenomena such as precipitation, phase transformation and recrystallization [11–13]. Applied to magnetic ageing, it can describe the evolution of the volume fraction of precipitates as a function of time. This model considers isothermal conditions and homogeneous nucleation. This implies staying in the same kinetics of precipitate formation which seems to be the case for the M600-65A grade but not for the M400-65A grade at 160 °C when compared to 180 °C and 200 °C. The analytical expression of the model is given in Eq. (1).

$$Y(t) = 1 - e^{(-(k \cdot t)^n)} \tag{1}$$

The term $Y(t)$ is the rate of transformation. This rate represents the ratio of the volume fraction $Fv(t)$ of the precipitates at a given time t to the maximum volume fraction $Fv_{\max}$ reached at equilibrium. The parameter n represents the Avrami index ($1<n<4$) that depends on the nucleation nature (homogeneous or heterogeneous) and precipitate morphology. The parameter k is a frequency factor (s^{-1}) [14].

As detailed in [5], the JMAK model can be also applied to the iron loss evolution with ageing by considering, on the one hand, the proportionality between volume fraction and coercivity [4] and, on the other hand, the proportionality between coercivity and iron losses [6]. The associated rate of transformation Y_p is given in Eq. (2).

$$Y_p(t) = \frac{P(t) - P_{min}}{P_{max} - P_{min}} = 1 - e^{(-(k_p \cdot t)^{n_p})} \tag{2}$$

5. Model identification

In [14] the parameter n_p is described as not temperature dependent if the nature of the precipitates remains unchanged. According to the experimental results, the M600-65A grade tends to respect this hypothesis for the three considered temperatures, Fig. 4, unlike for the M400-65A, Fig. 5, where the kinetics of precipitation seem to differ at 160 °C. Thus, based on the literature, the Avrami index n_p is considered constant $n_p = n_{p0}$ and the parameter k_p is temperature dependent. These parameters are identified for each temperature, Table 1. The choice is made to also present the results for the M400-65A grade, although it is outside the model hypotheses, to see how the latter behaves.

Regarding the frequency factor k_p, this latter decreases significantly with the ageing temperature (see Table 1). Indeed, this parameter is expected to be temperature dependent [14]. The comparisons, for both grades, between the experimental measurements and the model are given in Fig. 6 and Fig. 7. Results show good agreement, even for the M400-65A grade.

Table 1
JMAK parameters for both studied electrical steel grades.

		Ageing @160 °C	Ageing @180 °C	Ageing @200 °C
M600-65A	k_p	2.91×10^{-6}	6.72×10^{-6}	1.05×10^{-5}
	n_p		1.592	
M400-65A	k_p	6.72×10^{-6}	8.63×10^{-6}	1.24×10^{-5}
	n_p		1.910	

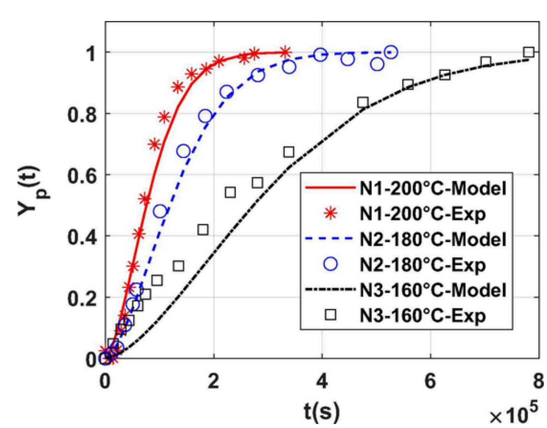

Fig. 6. JMAK model fitting and experimental measurement M600-65A, 1.5 T, 50 Hz.

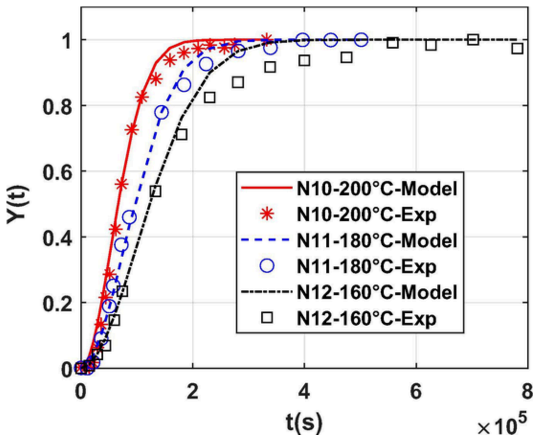

Fig. 7. JMAK model fitting and experimental measurement M400-65A, 1.5 T, 50 Hz.

The next step in the modelling phase is to couple the JMAK model with the Arrhenius' law to obtain the analytical expression of the iron losses as a function of time and temperature. This coupling is made through the parameter k_p defined in Eq. (2) using its values at the three ageing temperatures T_1, T_2 and T_3 to identify the Arrhenius' law given in Eq. (3). In this equation k_o is a constant (in s^{-1}), E is the activation energy (in J) of the transformation (precipitation) and k_B is the Boltzmann constant (1.38×10^{-23} J/K).

$$k_P(T) = k_0 e^{\left(-\frac{E}{k_B \cdot T}\right)} \begin{cases} k_P(T_1) = k_0 e^{\left(-\frac{E}{k_B \cdot T_1}\right)} \\ k_P(T_2) = k_0 e^{\left(-\frac{E}{k_B \cdot T_2}\right)} \\ k_P(T_3) = k_0 e^{\left(-\frac{E}{k_B \cdot T_3}\right)} \end{cases} \quad (3)$$

The parameters k_o and E are identified by linear regression after the transformation of Eq. (3) into the form $\ln(k_P) = f(1/T)$. The obtained values are summarized in Table 2 where E_m is the molar activation energy. Considering that the carbon theoretical diffusion energy in pure iron is about 80 kJ/mole [15] and that the studied electrical steels are not pure iron, the obtained order of magnitude is consistent with what is expected. In addition, the obtained energy of activation is lower for the grade M400-65A that showed the more pronounced ageing together with a higher rate of transformation observed at low ageing temperatures in comparison with the grade M600-65A. However, it is necessary to remain cautious about the obtained parameters for the grade M400-65A because, as mentioned previously, measurements show a different behaviour at 160 °C, probably due to a different precipitate nature.

Finally, by combining Eq. (2) and Eq. (3), it is possible to plot the transformation rate of iron losses for several durations and temperature levels, as shown in Fig. 8 for the M600-65A grade that satisfies the model assumptions. Very satisfactory results are obtained with this model that is able to represent the evolution of the transformation rate as a function of temperature. However, it should be noted that the identified model is only valid for temperatures for which the mode of precipitates formation is the same as that associated with temperature ranging from 160 °C to 200 °C.

Moreover, an analytical expression of the iron losses, as a function of temperature and time, can be derived from the previous considerations, as given in Eq. (4). The evolution of iron losses for several durations and temperature levels can therefore be known if the values of P_{max} and P_{min} are known. This presents a very interesting first step towards the modelling of the ageing of electrical steels under non-isothermal operating conditions.

Table 2
Arrhenius' law parameters.

	M600-65A	M400-65A
$k_o(s^{-1})$	13.43	107.2
E_m(kJ/mole)	55	26

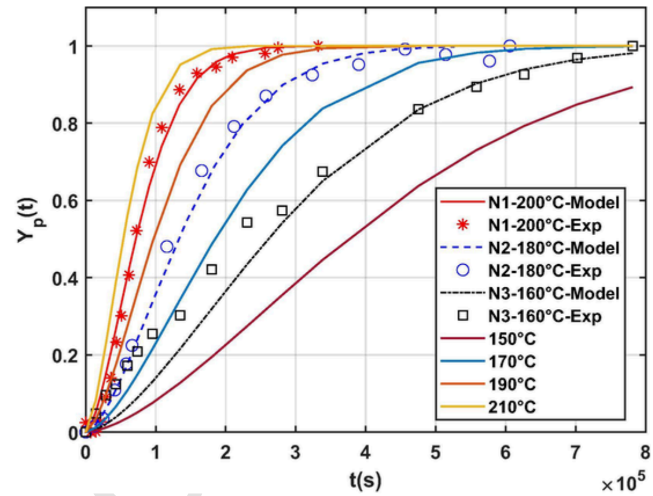

Fig. 8. Application of JMAK model coupled to Arrhenius' law for several temperature levels.

$$P(t,T) = (P_{max} - P_{min}) \left[1 - e^{\left(-k_0 \cdot t \cdot e^{\left(-\frac{E}{k_B \cdot T}\right)} \right)^{n_p}} \right] + P_{min} \quad (4)$$

6. Conclusions

In this study, the magnetic ageing of two electrical steel sheet grades (M400-65A and M600-65A) was treated at three temperatures: 160 °C, 180 °C and 200 °C. The observed magnetic ageing effect appears clearly for both grades although it is more significant for M400-65A grade. The behaviour is similar to those noted in previous researches except for the magnetic field magnitude, which shows a significant increase as a consequence of the magnetic ageing. In addition, the ageing effect always increases with the increase of the ageing temperature. Based on these experimental results, the Johnson – Mehl – Avrami – Kolmogorov (JMAK) law was applied to model the magnetic ageing effect on the iron losses for the three temperatures. Then, by coupling this model with the Arrhenius' law to describe the temperature-dependent parameter (frequency factor), an analytical expression of the losses as a function of time and temperature was deduced. The model shows also the ability to predict the ageing effect for any temperature within the range of temperatures used for its identification. However, for the M400-65A grade, the nature of precipitate formation seems to be different between the ageing temperature at 160 °C and the ones at 180 °C and 200 °C. This implies to be careful about the physical interpretation of the obtained model parameters. Therefore, concerning the M600-65A, the main perspectives are to apply and validate this model for non-isothermal temperature profiles and to include directly this model into an iron loss model (especially for hysteresis losses as in [5]). Modelling of the ageing effect on the normal magnetization curve must also be also addressed. Then, for the M400-65A grade, to the extent that it does not seem to be in the same kinetics mode at 160 °C, on the one hand, and at 180 °C and 200 °C, on the other hand, these results clearly highlight the importance of characterizing the precipitation state as a function of temperature. This latter aspect is the objective of a future work as well as the study of the link between the chemical composition, temperature and kinetics of precipitate formation (precipitates size, distribution, …).

CRediT authorship contribution statement

H. Helbling : Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing – original draft. **M. Toto-Jamil :** Conceptualization, Methodology, Writing – review & editing. **M. Dumont :** Conceptualization, Methodology, Writing – review & editing. **A. Benabou :** Conceptualization, Methodology, Writing – review & editing, Supervision, Project administration. **S. Clénet :** Conceptualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

[1] M.F. de Campos et al., "Consequences of magnetic aging for iron losses in electrical steels," J. Magn. Magn. Mater., vol. 304, no. 2, pp. e593–e595, Sep. 2006.

[2] J. de Oliveira Júnior et al., "Kinetics of Magnetic Ageing of 2%Si Non-oriented Grain Electrical Steel," Mater. Res., vol. 21, Oct. 2017.

[3] G. M. R. Negri et al., "Magnetic Aging Effect Losses on Electrical Steels," IEEE Trans. Magn., vol. 52, no. 5, pp. 1–4, May 2016.

[4] M.L. Néel, Nouvelle théorie du champ coercitif, Physica 15 (1) (1949) 225–234.

[5] M. Jamil and *al.*, "Application of the JMAK precipitation law in iron loss modelling to account for magnetic ageing effect," *J. Magn. Magn. Mater.*, vol. 547, p. 168901, Apr. 2022.

[6] G. Bertotti, Direct relation between hysteresis and dynamic losses in soft magnetic materials, J. Phys.Z Colloq. 46 (C6) (1985) C6–392.

[7] S. Nategh, H. Zhang, O. Wallmark, A. Boglietti, T. Nassen, M. Bazant, Transient Thermal Modeling and Analysis of Railway Traction Motors, IEEE Trans. Ind. Electron. 66 (1) (Jan. 2019) 79–89.

[8] S. Brisset, M. Hecquet, P. Brochet, "Thermal modelling of a car alternator with claw poles using 2D finite element software", COMPEL - Int J. Comput. Math. Electr. Electron. Eng. 20 (1) (2001) 205–215.

[9] L. Rodrigues, High-temperature embedded electric machines for aerospace turbine applications, University of Sheffield, Thesis, 2013.

[10] S.K. Ray, O.N. Mohanty, Magnetic ageing characteristics of low silicon electrical steels, J. Magn. Magn. Mater. 28 (1) (1982) 44–50.

[11] M. Avrami, "Kinetics of Phase Change, I General Theory" (1939).

[12] W.A. Johnson, "Reaction Kinetics in Processes of Nucleation and Growth", 1939.

[13] A.N. Kologomorov, "On The Statistical Theory of Metal Crystallization", 1937.

[14] D.A. Porter and K.E. Easterling ,Phase Transformation in Metals and Alloys, Edited by Chapman&Hall, 2nd edition, 1992, p. 290.

[15] M. Perez, A. Deschamps, Microscopic modelling of simultaneous two-phase precipitation: application to carbide precipitation in low-carbon steels, Mater. Sci. Eng. A 360 (1–2) (2003) 214–219.