# The classical losses in non-oriented steel sheets.

Carlo Appino[1], Hanyu Zhao (赵浛宇)[1,2,3], Carlo Ragusa[3], Mahmood Khan[1,3], Olivier de la Barrière[4], and Fausto Fiorillo[1]

*[1] Istituto Nazionale di Ricerca Metrologica, Nanoscience and Materials Division, Torino, Italy*
*[2]Province-Ministry Joint Key Laboratory of Electromagnetic Field and Electrical Apparatus, Hebei University of Technology,China*
*[3] Politecnico di Torino, Energy Department, Torino, Italy*
*[4] SATIE-ENS, UniverSud, Cachan, France*
*(h.zhao@inrim.it)*

## 1. Introduction

The theory of loss separation based on the Statistical Theory of Losses (STL) provides complete description of the frequency dependence of the energy losses in non-oriented soft magnetic sheets assuming uniform magnetization reversal throughout the sheet cross-section. This assumption has been recently challenged in the literature, in favour of a non-uniform reversal mechanism, expected to prevail, even in the absence of skin effect, in highly non-linear materials, where saturation magnetization wavefronts are estimated to symmetrically propagate across the sheet thickness (Saturation Wave Model, SWM) [1]. In this paper we discuss investigations on the broadband energy loss versus frequency behavior in different non-oriented Fe-Si and low-carbon steel sheets. The experiments are accurately and consistently described by the STL. This occurs, in particular, for high-induction values and near-squared hysteresis loops, a predictable condition for adopting the SWM, which fails instead to explain the experiments.

According to the STL, the concept of loss separation at a given frequency $f$ is expressed as $W(f) = W_h + W_{cl}(f) + W_{exc}(f)$ , with the measured loss is the sum of hysteresis $W_h$, classical $W_{cl}(f)$, and excess $W_{exc}(f)$ components. The classical loss component at frequency $f$ in a sheet of conductivity $\sigma$ and thickness $d$ is, in particular, obtained for sinusoidal induction of peak value $B_p$ as

$$W_{cl}(f) = (\pi^2/6) \cdot \sigma d^2 B_p^2 f \ . \qquad [\mathrm{J/m^3}] \qquad (1)$$

It has been pointed out in recent times that the use of (1) would not be a good approximation for $W_{cl}(f)$ in actual polycrystalline materials (e.g. nonoriented Fe-Si sheets) excited at technical $B_p$ values [1]. According to the SWM theory, the classical loss is best expressed at sufficiently high $B_p$ values as

$$W_{cl}^{(SWM)}(f) = \frac{\pi^2}{4} \cdot \sigma d^2 B_{max}^2 f \cdot \frac{B_p}{B_{max}} = \frac{3}{2} W_{cl}(f) \cdot \frac{B_p}{B_{max}} \ . \qquad [\mathrm{J/m^3}] \qquad (2)$$

where $B_{max}$ is taken as the peak induction where a near-rectangular DC loop is observed. Loss analysis based on (2) brings about a substantial change on the decomposition procedure envisaged by STL via (1) In order to clarify this matter, we have performed and analysed selected loss versus frequency measurements on NO Fe-Si and low-carbon steel (LCS) sheets at low and high $B_p$ values.

## 2. Methods and Results

Magnetic energy losses have been measured at various peak polarization levels $J_p$ from quasi-static conditions up to maximum frequencies ranging between 400 Hz and 10 kHz in nonoriented Fe-Si and low-carbon steel sheets, tested either as Epstein strips or ring samples by a calibrated wattmeter-hysteresisgraph under digitally controlled sinusoidal induction [2]. It is revealed by the experiments on non-oriented steel sheets

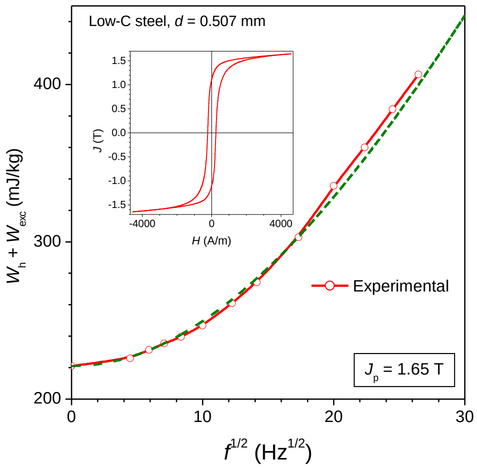


Fig. 1. Frequency dependence of the experimental quantity $W_h + W_{exc} = W - W_{cl}$, with $W_{cl}$ given by (1), versus the same quantity predicted by the STL model (dashed line). Predicted and experimental curves tend to slightly diverge beyond about 500 Hz, because of incipient skin effect. The inset shows the corresponding quasi-static hysteresis loop.

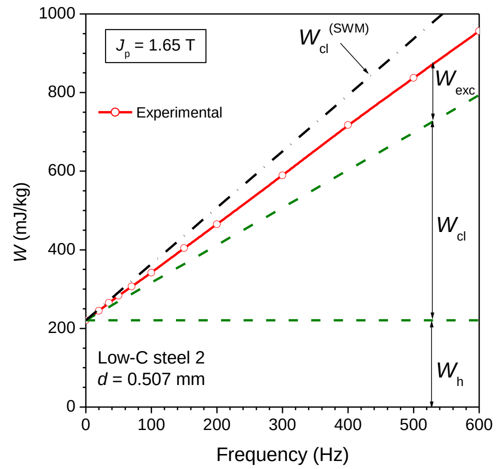


Fig. 2. Decomposition of the energy loss measured at $J_p = 1.65$ T in the sheet of Fig. 1. The classical loss $W_{cl}$ is obtained by (1). The dash-dot line is obtained calculating the classical loss $W_{cl}^{(SWM)}$ with (2) ($B_{max} = B_p$). $W_{cl}^{(SWM)}$ overestimates the measured loss.

that the magnetic energy losses can be assessed accurately at low and high inductions using the STL loss decomposition method. This is, in particular, achieved, within the constraints posed by the skin effect, assuming uniform reversal of the magnetization across the sheet cross-section at the macroscopic scale and the corresponding standard formulation (1) for the classical loss $W_{cl}(f)$. component. By making measurements up to $J_p = 1.65$ T in low-carbon steels, one can put in evidence, as shown in Figs. 1 and 2, that (1) still holds, although the $B(H)$ constitutive equation tends to emulate the step-like function invoked in (2), where the occurrence of the magnetization reversal by inward motion of one-dimensional fronts is envisaged [1]. The ensuing formulation for the classical loss turns however, as shown in Fig. (2), to largely overestimate the measured losses and should be ruled out.

### References


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