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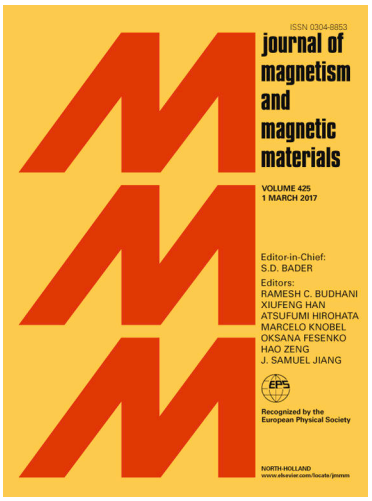

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Effect of mechanical cutting on the energy loss of laser-scribed grain-oriented alloys

Veronica Manescu (Paltanea)[a,b], Gheorghe Paltanea[a,*], Enzo Ferrara[c], Iosif Vasile Nemoianu[a], Fausto Fiorillo[c], Horia Gavrila[a]

[a] *University Politehnica of Bucharest, Faculty of Electrical Engineering, Bucharest, RO 060042, Romania, gheorghe.paltanea@upb.ro, paltanea03@yahoo.com*

[b] *University Politehnica of Bucharest, Faculty of Material Science and Engineering, Bucharest, RO-060042, Romania*

[c] *Advanced Materials Metrology and Life Sciences, Istituto Nazionale di Ricerca Metrologica—INRIM, 10135 Torino, Italy*

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Abstract

We investigate the effect of mechanical cutting on the magnetic properties of high permeability grain-oriented (HGO) laser-scribed Fe-Si sheets. Measurements have been performed on strips of different widths (5 to 60 mm) cut from 0.27 mm thick sheets. Normal magnetization curve and energy loss have been determined by means of a digitally controlled single strip tester from 1 Hz to 1 kHz at peak magnetic polarization values J_p = 1000 mT and 1700 mT. The results fit into a simple phenomenological model regarding the dependence of magnetization curve and energy loss on the strip width, in substantial continuity with the approach originally developed for non-oriented electrical steels. The hysteresis W_h and excess W_{exc} loss components are shown to depend on the strip width according to a hyperbolic law, with a limiting fully hardened strip predicted to occur for widths around 3.5 mm. It is then consistently observed that the mechanical cutting of standard 30 mm wide HGO Epstein strips is conducive to an increase of the energy loss at 50 Hz and 1.7 T of the order of 13 %.

1. Introduction

High-permeability grain-oriented (HGO) Fe-Si sheets are endowed with sharp directional texture and widely spaced domain walls. Consequently, they display excellent quasi-static magnetic behavior, but, because of the largely inhomogeneous magnetization process, the dynamic losses can increase. For this reason, laser scribing of the sheets, a non-contact technique smoothly incorporated in the production process, is applied to top-quality industrial products, in order to achieve, by a combination of local magnetostatic and magnetoelastic effects, a refinement of the domain structure [1, 2]. This treatment conveniently leads to a substantial decrease of the excess loss component W_{exc}, at the cost of a slightly increased quasi-static loss W_h [3, 4].

Sheet cutting, as required for the assemblage of the transformer cores, can partially impair, however, the excellent magnetic properties of these materials at the working frequencies. It is an effect descending from the residual stress induced by cutting along the strip edges and the ensuing additional magnetoelastic energy. A further complication arises with standard magnetic characterization of laser-scribed sheets by the Epstein method. In this case, scribing must be done on the cut Epstein strips after a stress-relief treatment, a cumbersome operation. On the other hand, there is no universal acceptance for the standard Single Sheet Test method (500 mm × 500 mm sheet) [5], while the suggested use of 100 mm wide strips in a giant Epstein frame is at the laboratory stage [6].

It is therefore important to know the extent to which the mandatory cutting operations deteriorate the dc and ac magnetic properties of the high-permeability GO sheets. Typical literature approaches look at the problem either from the viewpoint of quasi-static hysteresis modeling or of loss modeling by extensive use of numerical techniques [7–12], making the whole matter a quite complex affair. We have thus proposed in recent times a simple phenomenological model of the loss dependence on the width of non-oriented Fe-Si strips, obtained by guillotine punching and water cutting, based on the concept of loss separation [13, 14, 15]. Besides putting in evidence the extent to which W_h and W_{exc} are separately affected by the cutting operation, an estimate for the breadth of the strain-hardened region at the sample edges is made available. We show in the following that the very same physical concepts can be usefully applied to quantify the extent to which the punching operation can affect the magnetic losses of HGO Fe-Si sheets across a broad range of frequencies, up to 1kHz.

2. Materials and methods

Guillotine-punched strips of HGO laser-scribed Power Core-H-095-27, cut from a 0.27 mm thick parent sheet by a Krass Q11-2X2500 shearing machine, have been investigated. The clearance of the shearing machine was set at 35 μm, with punch radius 30 to 45 μm and surface pressure under the blank holder of 300 MPa.

300 mm long strips of width ranging between 5 mm and 60 mm were cut along the rolling direction (RD). They were characterized by means of a single sheet tester in the frequency range 1 Hz ≤ f ≤ 1 kHz at the peak magnetic polarization values J_p = 1.0 T and 1.7 T. A calibrated hysteresisgraph-wattmeter endowed with digital control of the sinusoidal induction waveform was used, where the magnetizing current is supplied by combination of an Agilent 33220 arbitrary function generator and a dc-coupled NF HSA4101 power amplifier, whereas signal acquisition and conversion are achieved by means of a 12-bit 500 MHz HDO4045 LeCroy oscilloscope.

The strips were placed side-by-side between the 120 mm × 30 mm pole faces of double-C laminated yoke, to form, whatever the strip width, a 60 mm wide sheet sample. The number of simultaneously tested strips accordingly ranged from 1 to 12. A constant magnetic path length of l_m = 240 mm, equal to the distance between the pole faces, was assumed in all cases.

The energy loss versus frequency behaviors were analyzed by identification of the hysteresis W_h, excess W_{exc}, and classical W_{cl} loss components [16, 17, 18]. W_h is obtained by extrapolating the measured loss to f = 0, while W_{cl} is calculated according to standard formulations [19], where a defined DC permeability value is assigned to the material for any J_p value. The skin effect, appearing beyond about 400 Hz, is in this way only approximately accounted for in the upper frequency range.

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3.1. Normal magnetization curve

The normal magnetization curve, measured up to the maximum field value H_{max} = 5500 A/m, shows the expected deterioration of the soft magnetic behavior engendered by cutting, which extends across the whole 0.02 to 1.95 T tested J_p interval. This is illustrated in Fig. 1 by the monotonical decrease of the material permeability upon the decrease of the strip width from 60 to 5 mm. This response is somewhat magnified with respect to the effect observed in non-oriented Fe-Si sheets. A same modeling scheme is here applied, where the cut sample of width w is described as made of an undamaged core region and two strain-hardened lateral strips of equal width L_c [13, 14, 17] (inset in Fig. 1). If J_P is the experimentally measured peak magnetic polarization, and J_{pc} and J_{p0} are the peak magnetic polarizations in the damaged ($2L_c$ wide) and undamaged ($w - 2L_c$ wide) longitudinal slabs, respectively, it follows from our scheme that these quantities are related by the equation

$$J_p(w) = J_{p0} - (J_{p0} - J_{pc})\frac{2L_c}{w}, \quad (w \geq 2L_c) \qquad (1)$$

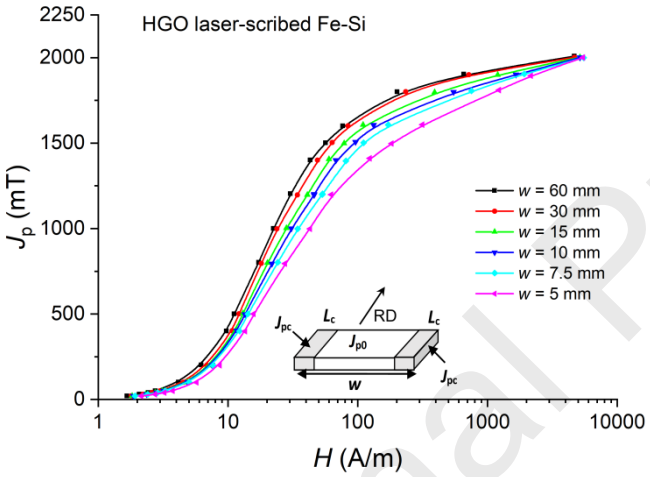

Fig. 1. Quasi-static normal magnetization curves versus width w of the punched strip samples (0. 27 mm thick HGO Fe-Si strips).

We consider Eq. (1) for a defined applied field H and write it as $J_p(w, H) = J_{p0}(H) - a(H)/w$, where we denote, in short, $a(H) = (J_{p0}(H) - J_{pc}(H)) \cdot 2L_c$. By taking two experimental reference $J(H)$ curves, taken on conveniently wide strips (for example, w_1 = 10 mm, w_2 = 30 mm in Fig. 1), the two quantities $J_{p0}(H)$ and $a(H)$ are calculated as a function of H. Table 1 lists the so-obtained values of $J_{p0}(H)$ and $a(H)$ for a broad sequence of applied field strengths, up to H_{max} = 5 kA/m. We introduce them in the previous equation and we obtain the dependence of the sample polarization $J_p(w)$ on the strip width at any chosen H value, as shown in Fig. 2 (solid lines). It is thus observed that the calculated curves excellently predict the experimental $J_p(w)$ values (symbols), derived from the ensemble of magnetization curves shown in Fig. 1. The vertical dashed line in Fig. 2 provides an estimate for the width $2L_c$ of the damaged lateral region. We make here an obvious simplification, where we neglect the blur accompanying the transition from the damaged to the undamaged regions. Looking at Fig. 2, we realize that $2L_c$ must be lower than 5 mm, the minimum investigated strip width (the experimental $J_p(w)$ is still decreasing). At the same magnetization curves, no more affected by cutting, coalesce, independent of strip width (see Fig. 1). The $J_p(w)$ curve calculated for H = 5 kA/m in Fig. 2 (the uppermost curve) must then be a constant quantity across all the w values, down to $w = 2L_c$. We can therefore confidently identify $2L_c$ with the coordinate in Fig. 2 where such a curve starts to decrease and falls into the forbidden region. We estimate in the present case $2L_c \sim 3.5$ mm. The peak polarization value pertaining to the damaged region is correspondingly identified, for any H value, by the intersection of the line $w = 2L_c$, with the theoretical $J_p(w)$ curves. By bringing then Eq. (1) to the limits $w = 2L_c$ and $w = \infty$, we can eventually predict the limiting curves corresponding to the fully work-hardened and the stress-free material, respectively.

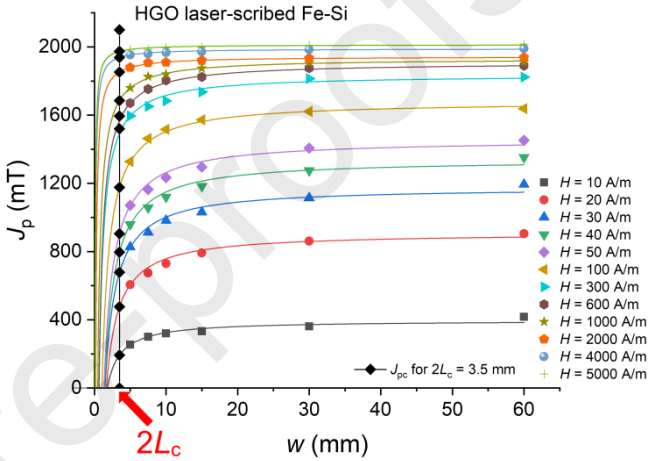

Fig. 2. Magnetic polarization J_p (symbols), measured at different field strengths in the 0.27 mm HGO Fe-Si samples, as a function of strip width w. The solid lines are predicted by the hyperbolic function (1). The vertical dashed line identifies the estimated width $w = 2L_c$ of the fully damaged strip.

Table 1. Behavior of the quantities a, J_{p0} and J_{pc} provided by Eq. (1) for different values of the applied field H.

H (A/m)	a (T·m)	J_{p0} (mT)	J_{pc} (mT)
10	0.0007	395.5	193.2
20	0.0015	909.8	476.5
30	0.0017	1177.2	678.1
40	0.0019	1340.3	796.5
50	0.0019	1456.7	905.3
100	0.0017	1680.3	1176.5
200	0.0013	1790.7	1392.3
300	0.0012	1835.7	1492.4
400	0.0012	1875.3	1520.2
500	0.0012	1892.2	1544.7
600	0.0011	1909.02	1569.1
700	0.0011	1922.8	1594.8
800	0.00105	1926.8	1624.7
1000	0.00086	1931.6	1685.9
1500	0.00051	1938.2	1790.3
2000	0.00031	1942.7	1852.7
3000	0.00021	1964.4	1902.8
4000	0.00017	1988.7	1938.2
5000	0.00013	2013.02	1993.7

3.2. The hysteresis energy loss

The hysteresis energy loss W_h, the quantity experimentally obtained by extrapolating the $W(f)$ curves to $f \to 0$, descends from the dissipation mechanisms related to the fast discontinuities of the domain wall motion (Barkhausen

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Following the previous schematic model of the cut strip, we describe, in analogy with Eq. (1), the quasi-static loss $W_h(w, J_p)$ per unit volume as the weighted sum of the contributions per unit volume W_{h0} and W_{hc} associated with the damaged and undamaged slabs, respectively

$$W_h\left(w, J_p\right) = W_{h0}\left(J_{p0}\right) + \left(W_{hc}\left(J_{pc}\right) - W_{h0}\left(J_{p0}\right)\right)\frac{2L_c}{w}, \quad (w \geq 2L_c) \tag{2}$$

where $W_{hc} \geq W_{h0}$ and the strain-hardened width $2L_c$ is already known from the previous analysis of the magnetization curves. We consider again the two previous reference strip widths w_1 and w_2 and the related $W_h(w_1, J_p(H_p))$ and $W_h(w_2, J_p(H_p))$ experimental behaviors. For any given H_p value we write Eq. (2) as

$$W_h\left(w_1, J_{p1}\left(H_p\right)\right) = a_1 + b_1\left(\frac{2L_c}{w_1}\right) \tag{3a}$$

$$W_h\left(w_2, J_{p2}\left(H_p\right)\right) = a_1 + b_1\left(\frac{2L_c}{w_2}\right), \tag{3b}$$

account being taken of the fact that, J_{p0} and J_{pc} (hence $W_{h0}(J_{p0})$ and $W_{hc}(J_{pc})$) are uniquely with known H_p value. This permits us to determine by Eq. (2) $W_{h0}(J_{p0})$ and $W_{hc}(J_{pc})$ for any defined w and J_p values. We can thus obtain the hyperbolic $W_h(w)$ behavior for any J_p as the volume-weighted sum of $W_{h0}(J_{p0})$ and $W_{hc}(J_{pc})$. This is shown, for $J_p = 1000$ mT and 1700 mT in Fig. 3, while the individual contributions by the pristine and strain-hardened regions are given in Table 2.

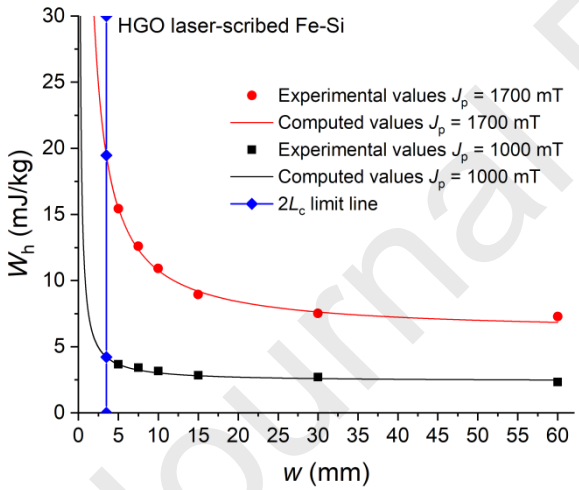

Fig. 3. Hysteresis energy loss W_h as a function of strip width w measured at J_p = 1000 mT and 1700 mT (symbols) and their prediction by Eq. (2) (solid lines). The lower limiting width $w = 2L_c$ of the fully damaged material is signaled by the blue line.

Table 2. Computed values of W_{hc} and W_{h0}.

J_p (mT)	W_{hc} (mJ/kg)	W_{h0} (mJ/kg)
1000	4.216	2.378
1700	19.464	6.057

3.3. Classical and excess energy losses

The statistical theory of losses [1] was applied to the analysis of the behavior of the measured $W(f)$ up to 1000 Hz. Fig. 4 illustrates such a behavior for J_p = 1000 mT and 1700 mT and the strip width w ranging between 5 and 60 mm.

$W_{cl}(f)$. This is associated with the macroscopic eddy current patterns, whose density increases from the sheet midplane to the surface according to a square law. Since the patterns are concentrated near to and at the surface, we conclude that $W_{cl}(f)$ is basically related to the flux derivative across the whole cross-section, that is, the average polarization J_p. It is additionally assumed that plastic straining does not affect the electrical resistivity. It is expected, however, that in the upper frequency range, beyond about 400 Hz, the flux penetration will be incomplete. Under such circumstances, the calculation of $W_{cl}(f)$ poses certain challenges in GO sheets [20]. We can approximately cope with this problem, provided the skin depth is not far from the specimen half-thickness (0.135 mm in the present case) by ignoring magnetic saturation and assuming an appropriate value $\mu(J_p)$ for the permeability, according to the standard formulation:

$$W_{cl}\left(f\right) = \frac{\pi}{2}\frac{\gamma J_p^2}{\mu}\frac{\sinh\gamma - \sin\gamma}{\cosh\gamma - \cos\gamma}, \quad [\mathrm{J/m^3}] \tag{4}$$

where $\gamma = \sqrt{\pi\sigma\mu d^2 f}$, σ is the conductivity and d is the sheet thickness [17]. We note that below f = 400 Hz, γ is low enough for Eq. (4) to reduce, once the material density δ is introduced, to

$$W_{cl}\left(f\right) = \frac{\pi^2}{6}\frac{\sigma d^2 J_p^2}{\delta} f. \quad [\mathrm{J/kg}] \tag{5}$$

Having calculated W_h and $W_{cl}(f)$, we remain with the excess loss

$$W_{exc}\left(f\right) = W\left(f\right) - W_h - W_{cl}\left(f\right), \tag{6}$$

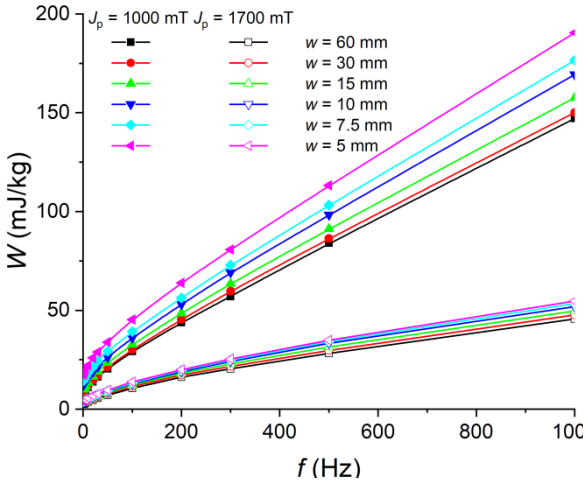

Fig. 4. Energy loss $W(f)$ measured versus frequency at J_p = 1000 mT and 1700 mT in punched 0.27 mm thick HGO Fe-Si strips. The strip width ranges between 5 and 60 mm.

that is, the extra dynamic loss engendered by the motion of the domain walls. The HGO sheets exhibit a wide domain spacing and $W_{exc}(f)$ can provide the largest contribution to $W(f)$ at power frequencies. The $W_{exc}(f)$ curves extracted from $W(f)$ using Eq. (6) are shown in Fig. 5. They follow an $f^{1/2}$ dependence and display an increasing trend under decreasing strip width, emulating to some extent the behavior of W_h. This is not surprising, because it is exactly what is predicted

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by
application to the theory of excess losses [19].

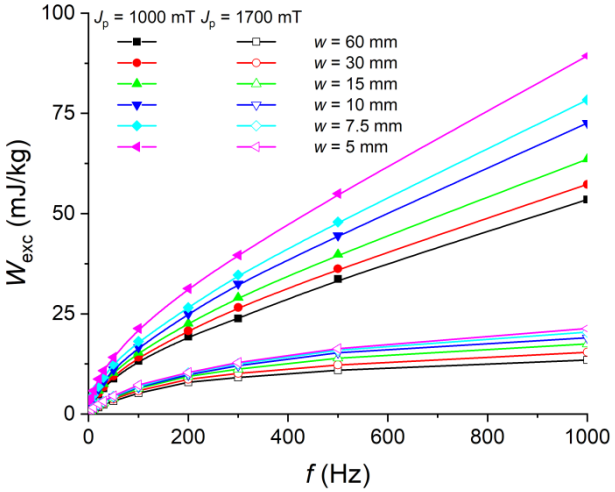

Fig. 5. Excess energy loss $W_{exc}(f)$ versus frequency at J_p = 1000 mT and 1700 mT in punched 0.27 mm thick HGO Fe-Si strips. The excess loss component $W_{exc}(f)$ is extracted from $W(f)$ according to Eq. (6).

$W_{exc}(f)$ is associated with the eddy currents circulating in the neighborhood of the domain walls. The mesoscopic character of these currents makes it possible to distinguish between the contributions to $W_{exc}(f)$ provided by the strain-hardened bands and the pristine core of the strip. This permits us to adopt the very same approach followed with the hysteresis loss and write at any frequency

$$W_{exc}\left(w, J_p, f\right) = \\ = W_{exc0}\left(J_{p0}, f\right) + \left(W_{excc}\left(J_{pc}, f\right) - W_{exc0}\left(J_{p0}, f\right)\right)\frac{2L_c}{w}, \quad (7)$$

with $W_{exc0}(J_{p0},f)$ and $W_{excc}(J_{pc},f)$ pertaining to the middle and the lateral bands, respectively. We shall consider again the experimental $W_{exc}(f)$ measured on the reference widths w_1 and w_2 and we shall repeat, for any selected frequency, the procedure previously devised for the determination of $W_{h0}(J_{p0})$ and $W_{hc}(J_{pc})$ versus w and J_p. Consequently, we arrive at predicting by Eq. (7) W_{exc} versus w, as shown, for selected frequency values and J_p = 1000 mT and 1700 mT, in Fig. 6.

As predicted by the theory, the increase of coercivity and hysteresis loss by mechanical hardening is attended by parallel, though somewhat mitigated, increase of the excess losses. The specific values $W_{exc0}(J_{p0},f)$ and $W_{excc}(J_{pc},f)$ found at f = 50 Hz for the two investigated polarization levels J_p = 1000 mT and 1700 mT are given in Table 3.

It is concluded that the measured loss $W(f) = W_h + W_{cl}(f) + W_{exc}(f)$ can be remarkably affected by mechanical cutting already at power frequencies, thanks to the increase by strain hardening of $W_h(f)$ and $W_{exc}(f)$. By the theoretical formulation one can predict, in particular, that around 13 % increase of $W(f)$ at 50 Hz and 1.7 T peak polarization is engendered in standard 30 mm wide Epstein strips.

Table 3. Computed values at 50 Hz of the two contributions W_{excc} and W_{exc0} for the polarization levels J_p = 1000 mT and 1700 mT

J_p (mT)	W_{excc} (mJ/kg)	W_{exc0} (mJ/kg)
1000	5.016	3.458
1700	16.586	8.453

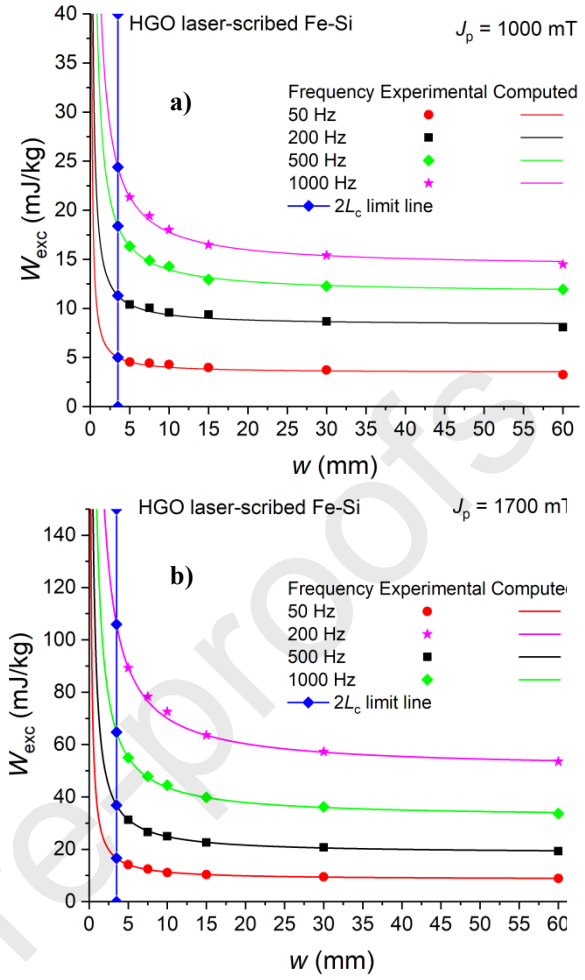

Fig. 6. Excess loss W_{exc} versus strip width in the punched 0.27 mm thick HGO Fe-Si strips. Solid lines and symbols refer to Eq. (7) and the experiments, respectively. Selected frequency values at J_p = 1000 mT (a) and 1700 mT (b) are considered. The intercepts of the vertical line with the $W_{exc}(w)$ curves provide the excess loss values pertaining to the $2L_c$ wide fully strain-hardened bands.

4. Conclusions

We have investigated the effect of mechanical cutting on the magnetization curve and energy loss of HGO Fe-Si steel sheets, by measurements on guillotine-punched strips of widths 60 to 5 mm between 1 Hz and 1000 Hz. A simple geometrical model, where the tested strip is composed of an unscathed core and two strain-hardened lateral bands permits one, in association with the loss decomposition procedure, to provide the analytical dependence of the hysteresis W_h and excess $W_{exc}(f)$ losses on the strip width. The formulation provides W_h and $W_{exc}(f)$ in terms of volume-weighted sum of the same quantities pertaining to the stress-free and the strain hardened slabs, respectively. A prediction can then be made of the evolution of W_h and $W_{exc}(f)$ as a function of the strip width, while estimating the breadth of the damaged region at the strip edges. Both loss components are observed to follow the predicted hyperbolic dependence on the strip width w, with an upper value attained for $w \cong 3.5$ mm (fully strain-hardened strip). It is concluded that in the unrelieved 30 mm Epstein strips the guillotine cutting leads to an increase around 13 % of the 50 Hz energy loss at 1.7 T.

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Highlights

1. Simple phenomenological model regarding the dependence of energy losses on the strip width
2. Simple phenomenological model regarding the dependence of magnetization curve on the strip width
3. Energy loss separation
4. Estimation of cutting damaged width strip

Declaration of interests

☒ 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.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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