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ORIGINAL RESEARCH

Standardisation concept for rapid testing of effects of cutting on losses of electric steel and amorphous ribbon

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Abstract

Soft magnetic lamination is produced with high width that usually is reduced by cutting. It yields permeability decreases Θ and loss increases r. So far, existing corresponding data is not consistent, since derived from strongly different lamination widths W. A consistent, ultra-rapid test method is suggested, for international standardisation. It is based on a multi-frequency single sheet tester. A 50 cm long, precisely prepared material sample of $W = 17$ cm is inserted into it, for an initial measurement in non-cut state. Then, it is cut into two 8.5 cm wide strips, for a test in cut state. Changes Θ and r are evaluated for induction values B up to 1.8 T. They are rapidly measured for frequencies of 50, 400 and 1000 Hz. Results from steel are described for guillotine cutting, from amorphous ribbon also for scissors. As a general tendency, Θ exceeds r by an order of about 3, however, with low reproducibility. Thus, standardisation is suggested for loss-rise functions $r(B)$ only. Examples of r-functions reveal strong individual differences, as foot-prints of different products. With increasing f, r-values tend to sink. With increasing B, they rise, except for high B of NO steel. Amorphous ribbon shows non-clarified deviating tendencies. Standardisation of r-tests promises comparable information on cutting effects, for a given material, through a given cutting tool—but also on the tool's state of wear.

KEYWORDS
amorphous magnetic materials, IEC standards, loss measurement, losses

1 | INTRODUCTION

Soft magnetic laminations are manufactured with high width W, partly even exceeding the order 1 m. Practical application for machine cores tends to need cutting to smaller dimensions. The corresponding procedures, like punching, guillotining or laser cutting, yield a deterioration of the material. It is located in close vicinity of the cut edge but also in the approaching areas of lamination.

During the last years, we focused our own work on a universal concept of standardisation of magnetic loss measurements by means of a physically consistent multi-frequency Single Sheet Tester (MF-SST) [1–4]. As an aim, it should offer highly defined - but rapid and simple - loss tests for the following two states of material:

(I) Measurement of losses P of a sample of material in ideal, "virgin" state—that is, in "green" state, as recently formulated in Ref. [5].
(II) Estimation of to-be-expected, relative loss-rises r, for the common case that the material is not applied in virgin state but is reduced by means of a given technology of cutting.

State (II) is the focus of the present paper.

In the last 30 years, international standardisations of loss testers were characterised by the dilemma of two different methods in parallel: the Epstein Tester (ET) [6] and the Standard SST [7]. Unfortunately, they yield loss results of significant difference. As a growing consent, the future should be focused on a *universal* test method that is physically consistent for all types of material, under different conditions. For example, this means that tests should be possible for all relevant levels of frequency f, as for example, needed for new developments of electric drives. But also assessments should be possible, for trimming the material to reduced widths, as needed for final application in core production.

Keeping the above global concept in mind, Refs [1–4] suggest for standardisation the aforementioned MF-SST. It can be applied for both crystalline electric steel and amorphous ribbon (AR), with a common sample length of 50 cm length. This rather high length favours representative results with respect to sample mass. This even is the case for reducing the usual SST-sample width of 50 cm by means of cutting. Here, it should be reminded to the fact that the IEC-Standard [7] fixes the length, but not the width.

Following a present general tendency of more compact testers, the sample width of MF-SST is reduced to 17 cm. Taking advantage of tolerances, this enables compatibility by cutting one 50 cm wide SST sheet into three MF-SST strips. The format is also compatible with the new IEC standardisation concept [8] of an SST with H-coil. It plans a sample of 50 cm length and "at least" 10 cm width.

Here, it should be stressed that the decision of 17 cm width of MF-SST sample was supported by the fact that literature points to w = 17 cm as the approximate starting point of "virgin" performance. This width corresponds to about 1% loss increase beyond the "unlimited width" case. For example, this is illustrated by fig. 2 of Ref. [9] and also by fig. 1 of Ref. [10].

With the above, the standardisation of tests on samples that fulfil requirements of "virgin" state can be assumed to be already initiated. On the other hand, so far, no activities are reported for standardised tests on materials that are cut to even smaller width.

Actually, a search of literature of the last decades reveals that scientific work on cutting rather is fully concentrated on the two following thematic:

(a) Attempts to get deeper understandings on consequences of cutting, with respect to regional deterioration of material.
(b) Establishment of analytical models for the prediction of consequences on permeability and losses, as a function of physical parameters.

On the other hand, attempts for a systematic assessment of cutting effects through standardised key quantities are missing, in complete ways. A search of literature reveals that the present paper represents a first proposal of a corresponding concept of standardisation.

2 | STATE OF THE ART

With the following, let us summarise the main topics of referenced studies in chronological ways. Already in 1977, Ref. [9] reported versatile effects of slitting on grain-oriented steel, for 50 Hz. Experimental results concerned rises of losses and decreases of permeability. The effects were attributed to plastic deformation of the cut edge, as well as to more-spread elastic stress. The dominant role of mechanical state was confirmed in several studies, like in Refs. [10–12]. Local analyses of cut lines revealed that a width of up to 2 mm tends to be strongly deteriorated [13, 14]. Later, it was emphasised that effects may spread out to adjoining sheet regions, by elastic stress, or through heat from laser cutting. Finally, spread was also attributed to displacement of magnetic flux, due to decreased permeability of the cut zone [15, 16].

In 2018, we started to focus our own work on the relevance of cutting for the *design* of loss testers. We observed that the ET is affected by extreme inhomogeneity of magnetisation, but even more by strong impact of strip cutting [17, 18]. Experiments and numerical modelling revealed that an extreme enlargement of ET would be necessary in order to reduce these side-effects. However, even doubling and tripling of strip width up to 10 cm [19, 20] yielded insufficient improvements. This was in agreement with the very informative study [9] of Z. Godez. It points to about 15 cm as being necessary to restrict cutting effects to an order of 1% loss increase, as an acceptable compromise for a loss tester. However, a width of 15 cm would yield an unacceptable size of ET. For us, this was a reason to give up the concept of ET in complete ways.

International tendencies to scale down the standard SST were a reason to concentrate on the MF-SST that uses a 30 cm long H-coil for physically consistent field detection [1]. Intensive studies led to an (unchanged) representative sample length of 50 cm. The sample width W was fixed to reduced 17 cm, in order to reduce slitting effects to an acceptable minimum, as indicated in Refs [9, 10]. As a further argument for 17 cm, it was chosen for possibilities to test three sample strips of MF-SST in a Standard SST, taking advantage from geometrical tolerances.

During the last years, international studies on cutting were intensified. Most are of analytical type [5, 21], or concerning modelling [22–26]. They make clear that a standardised assessment tool should be applicable for samples of all kinds of cutting tools. For example, it should be suitable for punching [27] and laser cutting [28], but also for water-jet [29] or electric wire discharge [25]. The result of testing should not be restricted to the closer cut-line vicinity. Rather, a sufficiently high sample width should consider thermally or elastically spread-out effects [9, 28]. As well, it should consider "indirect" effects that are originated from strongly reduced permeability of the cut line [28]. Finally, apart from low frequency, also intermediate frequencies of 400 Hz [27] or even kHz [26] should be considered, in particular with respect to compact motors.

The above cited studies confirm substantial progress towards a closer understanding of cutting effects. The results favour the establishment of models for the prediction of effects, as a function of physical parameters. However, the application of such models needs closer insight in physical mechanisms of basic nature. On the other hand, practical application in industry is disfavoured by the complexity of the high number of impact parameters.

In order to offer a practically relevant tool for the estimation of to-be-expected consequences of a cutting process, the present paper suggests the standardisation of a simple and rapid cutting test. A condition was that it can be handled by engineers, without needs of specific physical background and training.

3 | BASIC IDEA OF STANDARDISATION CONCEPT

Aiming for a simple and easy-to-be-interpreted methodology, a loss measurement series in non-cut (NC) state is compared with one in cut (C) state. Figure 1 illustrates the basic assumptions of the here suggested simple test procedure.

In some more detail, for a defined test of cutting effects, the following two-step procedure is suggested:

I. Measurement in NC-State—By means of the best available cutting tool of minimum wear, a "virgin" sample sheet is carefully prepared, with a length of 50 cm and a width of 17 cm width. Its losses *P* are precisely measured by an SST (like the already mentioned MF-SST).
II. Measurement in C-State–Then, the sample is cut in two 8.5 cm wide halves, by means of the two-be-assessed cutting tool. The two halves are re-inserted into the tester, parallel to each other. The results of the following test in the C-state are compared with that of NC-state.

As a matter of fact, a pre-requisite for the here proposed simple test procedure is the acceptance of the following convention: direct consequences of the preparation of the 50 cm × 17 cm sized "virgin" sample are neglected. This means that full effort should be made to avoid any damage of the sample's outer circumference lines. Experience shows that corresponding loss increases can be restricted to an acceptable order of 1%. This uncertainty finally defines the unavoidable basic error of testing.

Under the above consent, attention is fully concentrated on the to-be-assessed *central* cut line. Considering results from existing research (see also above references), this cut is expected to affect the sample, in the following ways (as schematically sketched in Figure 1.):

(i) The two edge regions along the central cut line are expected to exhibit plastic deterioration with strongly reduced permeability and increased losses.

These regions are expected to be restricted to a small width, of an order of a single millimetre. On the other hand, it is expected that the adjoining regions are affected as well, for possible distances of centimetres, in the following ways:

(ii) Elastic stress may arise, in particular from mechanical cutting like punching or guillotine.
(iii) Thermal deterioration is to be expected, in particular from laser cutting.
(iv) Increased flux density may arise, as a kind of flux-repel of the deteriorated edge zones.
(v) Third zones are to be expected, where the above effects can be neglected, from dominance of other impact factors.

The test procedure as suggested for standardisation restricts itself to the determination of the quantity losses *P*. However, *P* is determined as a *loss-rise function* of peak induction *B*. Such a function *r*(*B*) is characteristic for the response of a given material to a given - or projected - type of cutting procedure. The latter is defined by the cutting tool (e.g. a guillotine) and the cutting parameters (e.g. cutting speed).

Tests can be taken for different frequencies *f* of magnetization. This favours an understanding—or, at least feeling—for the responsibility of involved hysteresis effects or eddy current effects, respectively. In the following, examples of r-functions are given for 50, 400 and 1000 Hz.

Even an applier who uses his material for low frequency only, may take advantage from multi-frequency tests, due to deepened insight into the performance of his cutting procedure. A producer for rapid motors may restrict his tests to 1000 Hz, a priori. However, already here, it should be mentioned that testing by MF-SST yields an r-function *r*(*B*) within a single minute. This rapid performance stimulates and favours multi-frequency tests.

In principle, there is the possibility to apply the above procedure for arbitrary widths of virgin sample. However, this would yield a continuation of the present situation of slitting studies. The latter is characterised by high data on results from

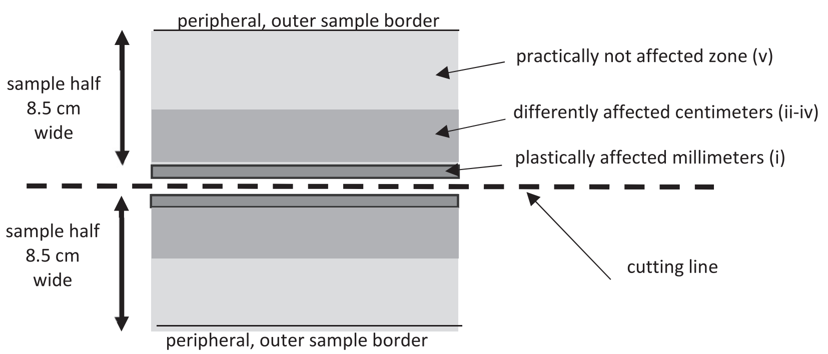

FIGURE 1 Assumption for a cut line, with zones that are deteriorated by plastic destruction (for mm width) and elastic stress + overload (for cm width) along it. See according regions (i) to (v) in the text.

very different cutting procedures. On the other hand, a standardisation of conditions will offer multiple, easily *comparable* data for different constellations of material versus cutting tool. Hopes exist for databases of material/tool combinations that are typical in industrial practice.

4 | EXPERIMENTAL

Figure 2a illustrates the experimentally applied magnetic test apparatus MF-SST and the location of non-cut sample in it. All technical details of apparatus are given in Refs [1–4]. Thus, we here restrict to specific aspects.

Starting the test, the "virgin" sample is inserted into the SST's sample tunnel, so that the sample's magnetised region of 45 cm length extends from the front pole face of magnetization yoke to the second back pole (Figure 2b). The yoke is manufactured from AR, thus allowing for magnetization frequencies f up to 10 kHz.

Using very precise synthetisation, a 28 cm long "detection region" of sample is magnetised in exactly sinusoidal ways (with Form Factor $FF = 1.111$). For the present application, the peak induction B was varied in steps of 0.1 T, for example, 0.5 T up to 1.8 T for grain-oriented (GO) steel, up to 1.6 T for non-oriented (NO) steel and up to 1.3 T for AR, respectively.

After ca. one minute, a protocol is print out. Apart from other data, it contains the here relevant about 10 values of peak induction B. For them, it lists the resulting values of permeability μ and losses P. Initial non-cut values are defined as B, μ_{NC} and P_{NC}.

As a next step, the sample is cut into the to-be-assessed C-state (Figure 2c). A second procedure of measurements is performed, resulting in a series of values μ_C and P_C (C indicating the state after cutting).

Finally, the cutting-induced percentage loss rises

$$r = [(P_C - P_{NC}) / P_{NC}]100\% \quad (1)$$

are evaluated, with NC for non-cut state and C for cut state.

In addition, our so far measurements included also a series of other characteristics. In particular, focus was put on (negative) relative changes of permeability μ, as expressed by the following equation:

$$\Theta = [(\mu_C - \mu_{NC}) / \mu_{NC}]100\% \quad (2)$$

Finally, also corresponding (positive) RMS-field changes were evaluated as follows:

$$\vartheta = \left[\left(H_{RMS,C} - H_{RMS,NC}\right) / H_{RMS,NC}\right]100\% \quad (3)$$

Already here, it should be stressed that the quantities ϑ and Θ proved to depend on many parameters, thus not being suitable as key-factors of a standardisation process (see Discussion).

On the other hand, the quantity r proved to show good repeatability and reproducibility, suitable as a characteristic for the cutting process, depending on material and cutting tool. In the present study, cutting of steels was performed with simple guillotines of 70 cm cutting length, in state of weak wear. Results for three types of material are reported in the following.

5 | RESULTS OF TESTING AND THEIR INTERPRETATION

The following reports results from a low-loss GO laser-scribed steel with stress coating and from two non-oriented steels. Further results concern Fe-based AR, as also being applicable for rather high frequency f, for example, for novel motors with high revolution. Finally, we also report multi-cutting to strips of small width, as needed, for example, for the preparation of Epstein samples, or for cores of small machines.

Already here, it should be stressed that the reported results are not assumed to be specifically representative for the corresponding types of material. Rather, they should demonstrate the to-be-expected orders of the loss-rise functions $r(B)$. And even more, they should visualise the ability of r-functions $r(B)$ to characterise the response of a given material to a given cutting procedure, in dependence of intensity of magnetization.

Apart from the scan of different values of peak induction B, r-functions are given for different values of frequency f. This should offer information for the practically given case of application, in particular, $f = 50$ Hz for conventional cores. Second r-functions concern the interim frequency of 400 Hz, as being relevant for air craft applications. Third ones concern the rather high value of 1000 Hz, as being of steadily increased relevance for drives of e-mobility.

5.1 | Results for grain-oriented steel

The following reports results of a highly grain-oriented steel that is laser-treated for domain refinement. Compared to considerably high thickness of the further down described non-oriented steels, the present one shows a thickness D of just 230 μm. Considering main applications for transformer cores, the here given magnetization conditions range up to an induction $B = 1.8$ T. We see results of loss rise functions $r(B)$, for the three further up mentioned frequency values $f = 50$, 400 and 1000 Hz.

Figure 3 shows that r increases with rising B, as a basic tendency. For 50 Hz, maximum r-values are indicated which however should not be interpreted as a poor performance of the given steel. On the contrary, outstanding developments of grain orientation for low hysteresis losses are coupled with domain refinement, for low eddy current losses. This performance is optimised for 50 Hz, linked with high induction B. This means that an advanced system is given here that is highly sensitive to deteriorated working conditions. Mechanical cutting disturbs these perfect conditions in multi-

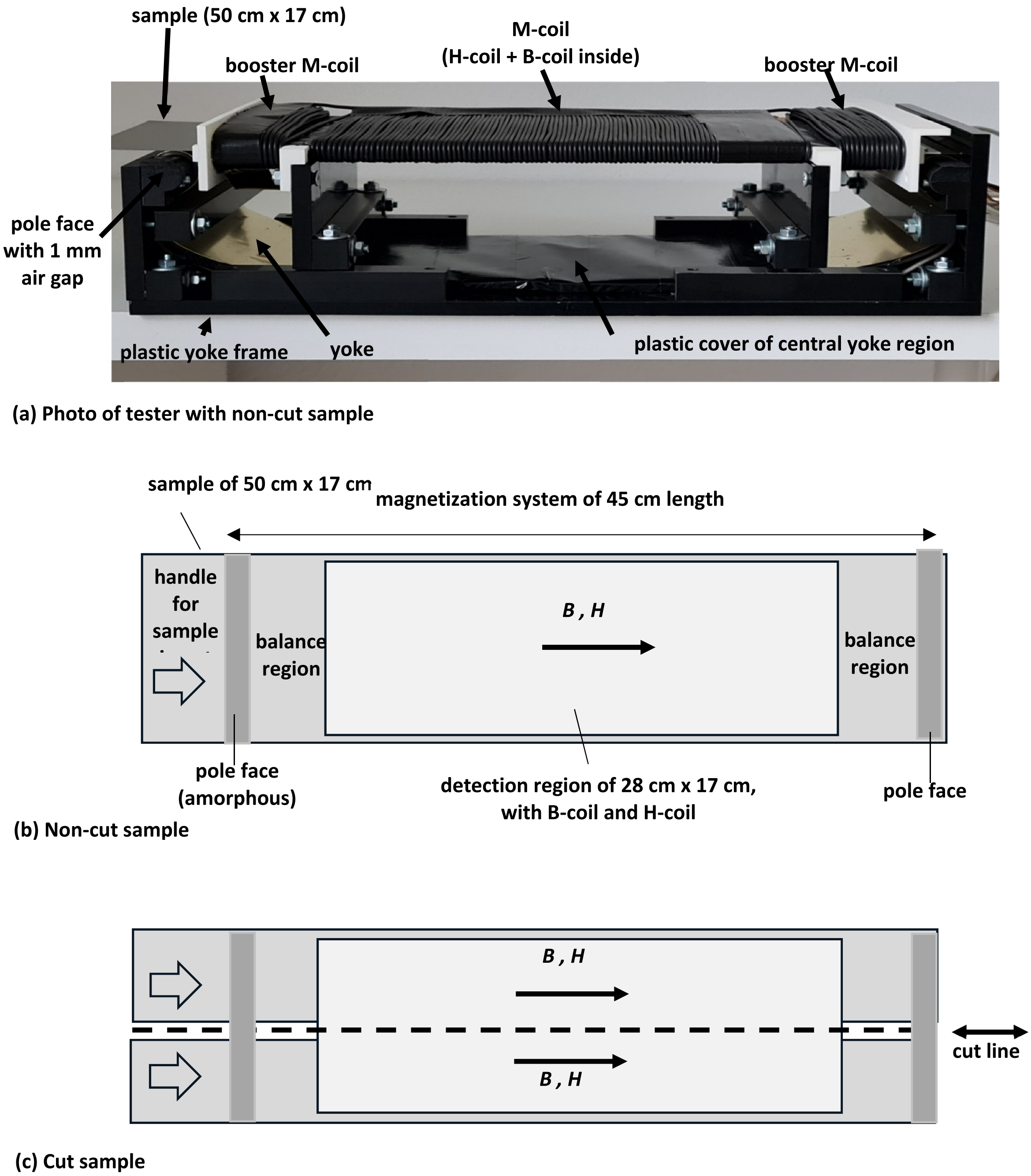

FIGURE 2 Schematic outline of test method. (a) Photograph of apparatus, seen from the side. (b) Sample of 17 cm width in non-cut state (NC), from above, sketched with strongly reduced width. (c) Two sample halves in cut state (c) of 8.5 cm width each.

parametric ways, which explains the rather high order of loss-rises r.

Analogous to the above interpretation, increased frequency is characterised by much lower sensitivity, r falling to values below 4% for 400 Hz. This is due to generally lowered cutting-sensitivity of eddy current losses. But the large difference is also due to the fact that the material is operated under non-optimised frequency conditions, a priori. Even higher frequency enhances the reduction, however, in mild ways. A closer interpretation of results would need challenging study that is not subject of this paper.

A practical assessment of results depends on the kind of application. Minimum impact exists for power transformers due to high widths, at least of central laminations. On the other hand, distribution transformer cores can be assumed to be affected, in particular laminations of outer core packages.

A case of highest relevance is given for samples as prepared for loss testers. Square 50 cm samples of standard SSTs are wide enough to be unaffected. On the other hand, samples of narrow strip testers are affected, and in particular just 3 cm wide Epstein strips [6]. Annealing is possible, but may affect

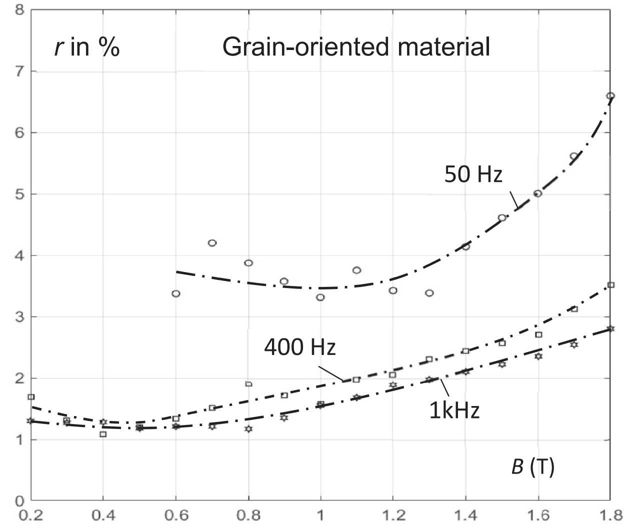

FIGURE 3 Percentage loss rises r for highly grain-oriented steel, as a function of induction peak value B, for three values of frequency f.

the characteristics of material with respect to stress coating or laser scribing (see IEC document [30]).

5.2 | Results for non-oriented steel

As a first example for NO steel, we selected for Figure 4a a conventional one with thickness $D = 350$ µm and rather high losses $P = 2.85$ W/kg (at $B = 1.5$ T, for $f = 50$ Hz). To cover the practically relevant operation range (e.g. for e-mobility), we performed some tests also for induction B up to 1.6 T.

Similar to the GO-case of Figure 3, we see rises of r for increasing induction B also here. With about 5%, also the order of rises proves to be comparable. However, contrary to the GO-case, approaching saturation is characterised by decreasing effects.

This rather unexpected phenomenon was also reported in Ref. [28] (see fig. 8). For 50 Hz, it was reproduced for eight material types, however, for increases of field (see Section 6). Hypothetically, we assume that this is due to the following: Also in non-cut state, the magnetization in the here selected rolling direction has to be mediated by a substantial reconstruction of domain configurations, as a reason of high losses. The latter are affected by cutting in relatively weak ways.

The decrease of effects for high induction proved to be a repeatable finding. For a confirmation, we investigated a second type of NO steel. We selected a more novel one with thickness $D = 300$ µm and very moderate losses of $P = 1.88$ W/kg (at $B = 1.5$ T, for $f = 50$ Hz). Actually, the results in Figure 4b confirm those of Figure 4a in consistent ways, for all three f-values. However, as a significant difference, the material shows much higher sensitivity towards the given cutting procedure. Instead of r-values up to 5%, we see almost doubled maxima of the high order of 10%.

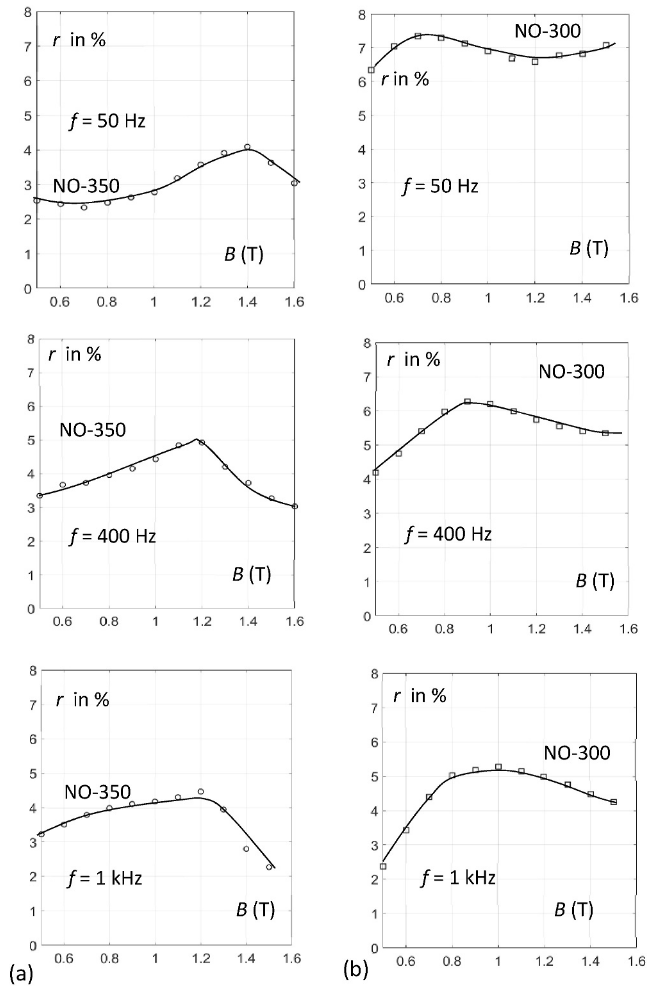

FIGURE 4 Percentage loss-rise functions $r(B)$ for two non-oriented steel types, for 50, 400 and 1 kHz. (a) For conventional NO-steel with $P_{1.5T, 50Hz} = 2.85$ W/kg. (b) For more advanced steel with $P_{1.5T, 50Hz} = 1.88$ W/kg.

As a rough interpretation, the more advanced NO-steel (in analogy to the further above discussed GO-steel) shows higher sensitivity towards disturbed working conditions. This sensitivity decreases with rising f. Obviously, sensitive hysteresis mechanisms here are dominated by eddy current mechanisms that are robust towards lattice defects and mechanical stress.

In contrast to the GO-steel type, loss rises r prove to be weakly affected by increases of frequency f. But according to recent studies [28, 29], interpretations are complicated by many impact factors like grain size, grain orientation (significant anisotropy also of NO-steels [2]), apart from the wear of cutting tool.

However, Figure 4 indicates that r may sink towards 2% for 1000 Hz, as being relevant for e-mobility. But weak relevance can be assumed, since high revolution with relatively high B can be characterised as a short-time event. As closely reported earlier in Refs [1–3], the corresponding losses reach extreme orders of more than 100 W/kg. In industrial practice, this tends to be considered through strong reduction of B, down to just some tenths of a Tesla.

5.3 | Results for iron-based amorphous ribbon

Tests were made for Fe-based AR (type 1k101), as delivered from China with 17 cm width, as being widely used for transformer cores. The test procedure comprised the following nine steps:

(i) Preparation of a sample of 50 cm length by means of scissors (or by guillotine); the cutting quality of shortening was irrelevant for test results, since affecting just the sample ends that remain outside the detection region of SST (Figure 2).
(ii) Placement of the sample in a V-shaped paper envelope (of 50 cm length and 17 cm width) for defined flatness and self-consistence, as closer described in Ref. [3].
(iii) Inserting the envelope + sample into the SST-slot, using the envelope end as a handle (Figure 2) that favours insert and pull back.
(iv) Performing tests in non-cut state (NC).
(v) After pull-out, cutting the sample into two 8.5 wide halves (optionally leaving a some centimetre long end in NC-state, to beware a unit that favours parallel arrangement, as well as simple archiving).
(vi) Replacement of the sample in the envelope (optionally with slight spot-wise fixation through some "drops" of Uhu Stick).
(vii) Re-insert of envelope with sample into the SST.
(viii) Performing tests in C-state.
(ix) Evaluating the resulting r-functions.

Due to very low sample cross section, tests at 50 Hz yielded very weak induction signals, as a reason for long duration of approximation. As discussed in detail in the amorphous-specific Ref. [3], exact loss determinations would need six ribbons, as a sample package of about 150 μm sum thickness. But this would restrict the attractiveness of corresponding cutting tests. However, experiences revealed that reliable r-functions result also from single-ribbon cutting. The reason is that Equation (1) yields the quantity r from the *ratio* of losses P. This means that absolute errors of P-measurement can be neglected.

Due to the above conditions, low-frequency tests were not made for 50 Hz, but for 100 Hz (for enhanced signal levels). Careful slitting of the sample was performed manually by commercial scissors (Solingen, of 26 cm length), exhibiting medium wear (without closer analysis). The total procedure time for (i) to (ix) proved to be below 30 min.

Table 1 summarises test results for a Fe-based sample, for peak induction values $B = 0.5$, 1.0, and 1.3 T. Apart from loss-rises r, also the corresponding loss values P_{NC} are listed, since not being of general knowledge, for the given amorphous material.

The results in Table 1 comprise measurements in the large loss range between 0.1 and 7.5 W/kg. Cutting effects are characterised by loss-rises r that range from zero up to more than 5%. In clear ways, r proved to *increase* with increasing frequency which needs closer study. As well, the dependence from peak induction proves to be irregular. Attempts for interpretations should be given in a separate paper, in order to avoid a distract from the present focus of standardisation.

As a main practical experience, tests on AR prove to be feasible in most simple and rapid ways. Not any modification of tester is needed. The usual, very simple arrangement of sample in an envelope [3] offers rapid tests of very good repeatability [4]. However, as already mentioned and closer outlined in Ref. [3], the arrangement of a single ribbon yields low absolute accuracy. It is sufficient for a *relative* comparison of two states, as performed here - but not for a reliable loss value in one.

All above so far reported tests concerned the case that a 17 cm wide sample is cut into two strips of 8.5 cm width, by means of a single process of cutting. However, in practice, much more narrow strips may be relevant, in particular for thin AR. An important example concerns the preparation of just 3 cm wide sample strips for tests with Epstein frame. It allows measurements for several kHz, also for the case of AR, as reported recently in Ref. [31].

For an assessment of corresponding effects, we cut a ribbon in strips of 17 cm/4 = 4.25 cm width, by three cutting processes (Figure 5). The left end of ribbon was remained in non-cut state to preserve a sample unit that can be handled in easy ways by insert into a sample envelope. Table 2 shows examples of corresponding rest results.

TABLE 1 Results for loss rises of an amorphous ribbon of type 1K101.

f		$B = 0.5$ T	$B = 1.0$ T	$B = 1.3$ T
100 Hz	P_{NC}	0.113 W/kg	0.280 W/kg	0.392 W/kg
	r	2.7%	1.8%	1.5%
400 Hz	P_{NC}	0.635 W/kg	1.58 W/kg	2.30 W/kg
	r	3.8%	2.1%	0%
1000 Hz	P_{NC}	1.99 W/kg	5.23 W/kg	7.50 W/kg
	r	4.0%	5.6%	5.5%

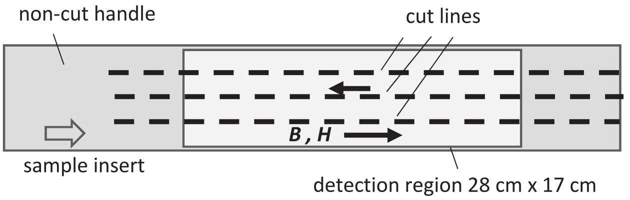

FIGURE 5 Sketch of sample that is treated by multi-cutting to four narrow strips of 17 cm/4 = 4.25 cm width each. The option is indicated to beware a non-cut left sample end.

As to be expected, the table indicates strongly enhanced consequences of the further reduction of strip width. Compared to 8.5 cm width (Table 1), reduction to 4.25 cm yields further increases of loss rises r, as a consequence of the introduction of two further cutting lines. In rough approximation, three-fold loss-rises confirm the basic tendencies of increasing loss-rises with increasing frequency. However, it is not planned—and not suggested - to include multi-cutting into attempts of standardisation, since it would threaten the basic idea of simplicity and transparency.

6 | ALTERNATIVE ASSESSMENT QUANTITIES

The above sections of results describe percentage increases r of *losses* as a result of cutting processes. As clearly indicated by literature (e.g. Refs [9, 10, 12, 27, 29]), an alternative would be to replace the measurement of losses P through tests of permeability μ. Experience shows that μ tends to be influenced by cutting in more pronounced ways.

The present study was focused on losses. But most tests included also changes Θ of permeability μ, according to Equation (2). Here, μ was defined from the ratio of peak values B and H. In addition, changes ϑ of the RMS-value of the magnetic field strength were evaluated, according to Equation (3).

Table 3 shows examples of results for a sample of the tested NO-steel of 300 µm thickness. As visualised by Figure 4, the steel shows an almost constant r-function for 50 Hz. This is confirmed by data in Table 3. On the other hand, we see that the field-related quantities change with about three-fold intensity. In principle, this promises strongly increased sensitivity of testing. However, the field-related parameters tend to be characterised by strong variations, in particular as a function of induction.

Our own tests confirm results of literature, that report momentum-changes Θ of high intensity. For example, Ref. [9] reports many examples that include ratios like the following: $r = 22.8\%$ versus $\Theta = 78.8\%$; $r = 14.9\%$ versus $\Theta = 67.9\%$. The changes ϑ are not identical, since Θ is based on the field's peak value, while ϑ concerns the RMS-value. This means that field-related quantities are not suitable for a reliable characterisation, in the framework of the here aimed-for standardisation. As a conclusion, focus should be put on losses—a quantity that also shows highest practical relevance.

Summarising, the following reasons speak for loss-rises r as an assessment quantity:

(a) Higher practical relevance, as also expressed from the entirety of the above Refs [9, 10, 12, 27, 29].
(b) Lower scatter of results, Θ and ϑ proving to be more sensitive to various other impact factors.
(c) Higher uniqueness, in comparison to the quantities "permeability" or "field". The latter may concern evaluations from peak values of induction and field, peak values of induction and RMS value of field (see product catalogues), or also differential, absolute or relative expressions, respectively.

All aforementioned yields the conclusion that a standardised test should be restricted to the determination of rises r of *losses*. As a significant advantage, already existing, applicable test apparatuses like [1] show very low values of all three repeatability errors (<0.2%), reproducibility errors (<1%) and absolute uncertainty (<3%), as closer discussed in Ref. [4]. But as a main reason, standards should be clear and compact. Also the standards [6–8] are clearly focused on losses, and not on field or permeability. A standard for cutting assessment should serve as a supplement to Refs [6–8].

7 | DISCUSSION

Prior to a closer discussion of results, it should be stressed that the accuracy of the here proposed procedure is - a priori - restricted to the preparation quality of the "virgin" sample sheet of 17 cm width. On the other hand, the repeatability of

TABLE 2 Loss rises r for amorphous ribbon, cut down to 4.25 cm.

Frequency f	$B = 0.5$ T	$B = 1.0$ T	$B = 1.3$ T
100 Hz	6.0%	5.6%	5.8%
400 Hz	11.6%	7.7%	4.6%
1000 Hz	12.3%	13.4%	16.2%

TABLE 4 Observed orders of loss rises r, for $B = 1$ T, for different types of tested materials (all cut from 17 cm down to 8.5 cm).

f	GO steel	NO(low μ)	NO (high μ)	Amorphous ribbon
50 Hz	4%	3%	7%	2% (100 Hz)
400 Hz	2%	4.5%	6%	2%
1000 Hz	1.5%	4%	5.5%	5%

TABLE 3 Effects on losses, permeability and RMS-value of field (for NO-steel) for 50 Hz.

	P (W/kg)		r	μ_r (−)		Θ	H_{RMS} (A/m)		ϑ
B (T)	NC/C	C	NC/C	NC/C	C	NC	C	NC/C	NC/C
1.5	1.88	2.00	6.3%	2080	1590	−24%	205	271	31%
1.3	1.27	1.36	6.4%	9350	7180	−23%	111	144	30%
1.0	0.74	0.79	6.8%	18,710	15,120	−19%	31.7	36.1	24%
0.8	0.50	0.53	6.0%	19,500	16,860	−13%	26.5	29.3	16%

results proves to be high, besides from consequences of irregular splitting procedures. However, the neglect of corresponding a priori cutting effects is a convention that hardly can be avoided, if a simple-to-be-performable, transparent test should be developed for standardisation.

The results of the present paper illustrate that the resolution of the here suggested test method is capable to differentiate specifics of different materials. For an illustration, Table 4 compares typical orders of loss-rises r for the analysed types of materials.

It should be stated that the method also proves to be a simple help in order to assess the instant *quality* of a given cutting tool. For example, Table 1 shows results of cutting for an Fe-based AR by means of high-quality scissors. Comparative cuts by low-prize scissors indicated the decreased quality in clear ways, through increased r-functions. Closer discussions will be given elsewhere.

The practical relevance of the test procedure is versatile, comprising the following, among others:

(a) The assessment of cutting tools for the preparation of magnetic test apparatuses, like Epstein frame or SST.
(b) The estimation of consequences on components of machine cores, as prepared by a given cutting tool.
(c) Qualitative assessment of the state of a given cutting tool, with respect of wear.
(d) Support for basic research on a closer understanding of cutting consequences.

Summing up, the here proposed procedure is simple and rapid. It yields easy-to-interpret, compact loss-rise functions r (B) that seem to range between 0% and about 10% - as easily-to-remember characteristics. Thus, the methodology is promising to be adequate for a possible international standardisation. A need for it results from the present situation that is characterised by the following:

I. The development of excellent materials of all types—grain-oriented steel, non-oriented steel and AR—offers soft magnetic laminations of optimum characteristics in non-cut, "virgin" state.
II. However, these good characteristics are partly lost after reducing the width by cutting—in rather hidden ways.
III. The so far reported investigation of effects was performed in multiple ways, but with completely inconsistent test conditions and with strongest variations of slitting widths. They are described by assessment parameters that tend to be inconsistent and complex.
IV. The so far 30 years of investigation are of very restricted help for industry. Academic results even do not clarify rough tendencies and orders of effects.
V. For the first time, the here-described universal test methodology promises standardised tests. They can be performed with generally available test apparatuses that yield compact loss-rise functions for a given material that is cut with a given cutting tool.

AUTHOR CONTRIBUTIONS

Helmut Pfützner: Conceptualisation; writing – original draft. **Georgi Shilyashki**: Investigation; software; visualisation. **Neofitos Christodoulou**: Validation.

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CONFLICT OF INTEREST STATEMENT

The authors describe no conflict of interest.

DATA AVAILABILITY STATEMENT

Protocols of measurements are available of reasonable request.

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