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TECHNICAL REPORT

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Studies and comparisons of magnetic measurements on grain-oriented electrical steelsheet determined by the single sheet test method and Epstein test method

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Studies and comparisons of magnetic measurements on grain-oriented electrical steelsheet determined by the single sheet test method and Epstein test method

INTERNATIONAL
ELECTROTECHNICAL
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INTERNATIONAL ELECTROTECHNICAL COMMISSION

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STUDIES AND COMPARISONS OF MAGNETIC MEASUREMENTS ON GRAIN-ORIENTED ELECTRICAL STEELSHEET DETERMINED BY THE SINGLE SHEET TEST METHOD AND EPSTEIN TEST METHOD

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The text of this technical report is based on the following documents:

Enquiry draft	Report on voting
68/535/DTR	68/543/RVC

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

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STUDIES AND COMPARISONS OF MAGNETIC MEASUREMENTS ON GRAIN-ORIENTED ELECTRICAL STEELSHEET DETERMINED BY THE SINGLE SHEET TEST METHOD AND EPSTEIN TEST METHOD

1 Scope

This document, which is a Technical Report, provides the results of international exercises and comparisons focusing on achieving the knowledge of the statistical performance of single sheet tester (SST) measurements made on grain-oriented electrical steel. These experiments aim at specifying obligatory reference values, measured by the single sheet test method, for the grading of high permeability (P grades) grain-oriented (g.-o.) materials, independently from the Epstein classification as it is practiced today. Besides this, Epstein test measurements have been made in order to gain more up-to-date statistical performance for comparison with the SST statistical characteristics. A few experiments were carried out aiming at improved knowledge on the systematic error performance of the SST, i.e. they were to determine the correlation between the quality of insulation separating laminations in the SST yokes and the measured loss.

There are various designations for "non-oriented electrical sheet steel" and for "grain-oriented electrical sheet steel" in use, for example in the IEC 60404 classification and specification standards, and there are also abbreviations like CGOS (for conventional grain-oriented steel) often used in industry. In this report, the following designations and abbreviations are used:

- electrical steel as generic term;
- n.-o- electrical steel and g.-o. electrical steel as generic terms for these two types;
- S-type electrical streel or c. g.-o. electrical steel for "conventional grain-oriented electrical steel";
- P-type g.-o. electrical steel or high-permeability g.-o. electrical steel;
- DR g.-o. electrical steel for "domain refined grain-oriented electrical steel";
- where two terms are used, it can depend on the context;
- "electrical steel" can be replaced with "material", depending on the context.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

IEC 60050-121, *International Electrotechnical Vocabulary – Part 121: Electromagnetism* (available at http://www.electropedia.org)

IEC 60050-221, *International Electrotechnical Vocabulary – Chapter 221: Magnetic materials and components* (available at http://www.electropedia.org)

3 Terms and definitions

For the purposes of this document, the terms and definitions given in IEC 60050-221 and IEC 60050-121 apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

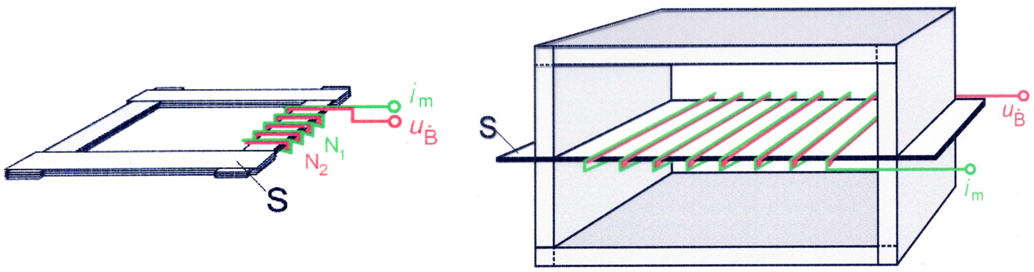
4 Background

4.1 Historical background and former concepts of the SST-Epstein relationship

The magnetic characteristics of electrical steel are significant in two regards. Firstly, they are decisive for the possible applications of the material. Secondly, the magnetic loss performance is essential for the material grading and for the efficiency of the energy transformation, i.e. for the energy costs and the economic and environmental aspects.

The Epstein method [1][1] and the single sheet tester (SST) method [2] are the two standardized methods for measuring the magnetic properties of electrical steel. Whilst the Epstein method, based on the 25-cm-frame, was designed about 60 years ago, the first edition of the single sheet tester standard was published in 1982 after intense discussions at IEC meetings (see Figure 1). This SST(82) standard comprised 500 mm x 500 mm sheet samples forming the closed magnetic circuit together with two symmetrical flux closure yokes made of grain-oriented electrical steel or nickel iron alloy. This first 1982-version was characterized by reference to the Epstein test method, i. e. it had to be calibrated using Epstein strips, 50 cm long and 30 mm wide, measured in the Epstein square and then, inserted side by side, in the SST. This method turned out to be considerably dispersive for reasons which are mentioned in 4.2 and 5.4.

Therefore, 10 years later, IEC published the independent single sheet test method in the IEC SST(92) standard [2] that includes the use of a conventional effective magnetic path length of l_m = 45 cm. However, due to the different designs of their magnetic circuits, SST(92) and Epstein methods show, in particular with high grade GOES materials, significant differences of their results when applied to the same material (for details, see 4.2).



Key

N_1 magnetizing winding

N_2 secondary winding

Figure 1 – Epstein frame and single sheet tester, schematic view, windings partly omitted

The Epstein method has been in use continuously, from its beginning to the present time, defined as the only reference method determining the quality reference in the specification standard. Correspondingly, the grade designations are directly related to the Epstein loss values, for instance the designation M150-35S5 designates a conventional (S-type) grain-oriented steel of 0,35 mm thickness with a maximum specific loss value of 1,50 W/kg measured by the Epstein method at 1,7 T and at 50 Hz. Thus, Epstein loss values have been the reference values for trade and application purposes, laid down in the lists of the

[1] Numbers in square brackets refer to the Bibliography.

specification standards, for about 60 years. For this reason, the Epstein to SST relationship was the subject of intense studies during the last two decades [3] [4] [6]. These studies are described in detail in Clause 5.

It is not easy to change this situation although the SST method is superior when applied to grain-oriented electrical steel because of its practical simplicity (no stress-relief annealing of sample needed) and also its suitability to the highest grade materials (e.g. domain refined grades which do not withstand stress relief annealing without deterioration of their properties). Therefore, an increasing part of the industry involved requests that SST reference values be included in the specification standards for these material grades [5].

4.2 Establishing reference values for grain-oriented electrical steels determined by independent SSTs – A new approach to the purpose

Earlier studies always based their considerations of the Epstein to SST relationship on the following formula:

$\delta P_{SE} = (P_{SST} - P_{Ep}) / P_{Ep}$ (or on the equivalent ratio P_{SST} / P_{Ep}).

The different systematic error characteristics of the Epstein and SST methods with grain-oriented materials can result, for instance, in differences of 4 % to 10 % between the specific total loss values, P_S, measured by them at a peak magnetic polarisation of 1,7 T. The systematic errors were found to be caused by the different magnetic circuit designs of the two methods, i.e. the inhomogeneity of the Epstein circuit formed by the double-overlapping joints of the strips (decrease of value), and, on the other hand, by the loss contribution through the SST yokes (increase of value).

Above, the main sources of systematic errors of both, Epstein and SST, are mentioned. Whilst systematic errors might be partly explainable, the statistical errors (dispersion), which are almost of the same magnitude for Epstein and SST, can only partly be assigned to specific phenomena. However, the Epstein to SST ratio, showing pretty good agreement between laboratories when identical samples are circulated, shows significant higher dispersion when the comparison refers to varieties of samples of the same grade (see for example 5.1). The intrinsic properties of those sample individuals are supposed to vary to an extent which is determined by the complexity of the process of sample preparation. Thus, it is probable that there is a significantly larger dispersion with Epstein samples rather than with SST samples (see also Figure 8 and [11]).

Recently, initiated through experts from industry closely involved in practical metrology [5], the awareness has grown that the Epstein to SST relationship, comprising the systematic and statistical error performance of both, Epstein and SST method, is an improper quantity for upgrading the SST to a reference method for high grade g.-o. electrical steel. The main reason is a phenomenon which was ignored with the studies published earlier, including the empirical SST-Epstein relation curve shown in Annex C of [2] which was obtained predominantly for conventional grain-oriented material. This phenomenon is the uncertainty that has to be assigned to the preparation of the Epstein strip samples which necessitates a stress relief annealing operation. This suppresses eventual internal stress due to the production process and, thus, has a misleading impact on the Epstein to SST relationship. This effect is more pronounced with high permeability g.o. material. This uncertainty accounts for a dispersion component of the properties of individual Epstein strip samples caused by the difference in the preparation procedures between laboratories and the randomly arranged strips in the sample stack. Items causing this dispersion component are the following.

Firstly, cutting the plate into strips creates basically a specimen with different properties: the flux is constricted to the strips. High permeability grades partly have grain sizes larger than the Epstein strip width. Flux paths in legs and corners of the strip's stack then undergo drastic changes compared with the entire sheet, and they depend on the random stacking. Internal stress is introduced through the cutting which shall then be removed through suitable annealing. Variations in this procedure create further dispersion:

– the method of cutting and sharpness of the cutting tools;
– the shape of the annealed samples – single strip or stack, with or without weight;
– the annealing procedure – duration, temperature, atmospheres, type of furnace;
– the handling of the samples.

This dispersion is not reflected by comparisons based on circulation of identical Epstein samples to the participating laboratories as it was practiced in the past.

However, this consideration does not include the still more complicated situation with domain refined grades which do not withstand stress relief annealing without deterioration of properties (see below).

In the case of non-domain-refined grades, the cutting to Epstein strips and the process of annealing the strips can, as mentioned above, change the intrinsic properties of the original product; in particular, it can make an inferior quality product which includes severe internal stresses seemingly better by releasing the stresses. This might be tolerated where the building process of the transformer core involves an annealing stage (e.g. wound cores). For manufacturers of stacked transformer cores, this is unacceptable [4].

Whilst companies having stable production processes and applying constant sample preparation may achieve a reasonable in-house-reproducibility of the Epstein method, this is not sufficient for the grading metrology worldwide. Generally, it can be stated that the higher the grade, the stronger is the influence on the dispersion from the Epstein sample preparation.

Finally, with laser domain refined materials, the Epstein test is even not applicable without an expensive wire cutting of the strips to avoid stress. Also, in this case, a certain dispersion caused by the different variations of the process of the Epstein sample preparation may be assumed, however there is no information which allows to quantify this. What remains is the random flux path fluctuation when large-grain material is cut to strips as was mentioned above.

Thus, if single identical Epstein sample stacks are passed through various laboratories, a small dispersion of the measured specific total loss does not tell us the full story. This might also hold for SST samples, however to a smaller extent, because they are prepared in only one step, the cutting. The items listed above suggest that the sample preparation procedure makes the Epstein method results inappropriate as a reference for the conversion into nominal SST values to be listed as specification of grain-oriented material of higher grades. Thus, the independent SST method according to IEC 60404-3 [2] is needed as the more appropriate method for this purpose. This will become more evident by the results shown in Clauses 5 and 6.

5 Preliminary comparisons and experiments

5.1 General

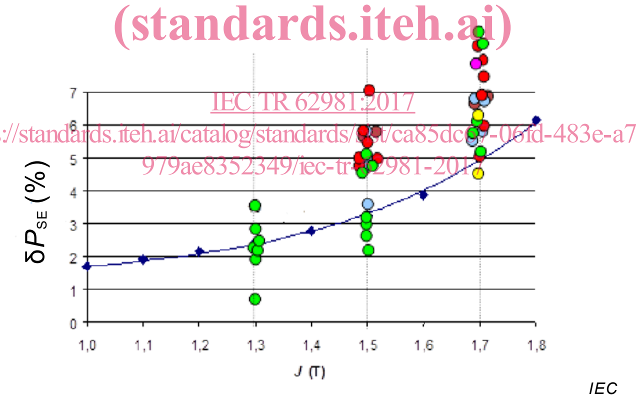
In the first phase of this IEC project, a comparison of the relative difference $\delta P_{SE} = (P_{SST} - P_{Eps})/P_{Eps}$ measured by steel manufacturers on their own products using their own set-ups was performed. It turned out that the information was not sufficient for specifying reference values for SST sheet samples (see 5.2 and 5.4).

In order to assess the influence of the yokes on the SST measurement results, further preliminary comparisons and experiments were subsequently made in China. Four laboratories and six SST fixtures with yokes having stacked lamination were involved. These experiments were to improve, besides the knowledge about the dispersion, the knowledge of the systematic error performance of the SST which becomes more significant when SST results would be upgraded to independent reference values (see 5.3 and [18]).

5.2 Comparison of the relative difference $\delta P_{SE} = (P_{SST} - P_{eps})/P_{Eps}$ measured by steel manufacturers on their own products using own set-ups

In 2012, seven manufacturers took part in this exercise and made their data measured on related pairs of Epstein and SST samples available for comparison. Two of them contributed data measured on non-oriented materials of grades 270-50A, 400-50A, 470-65A, 600-50A and 700-50A (5 sample pairs each). These δP_{SE} results turned out to be between +14 % and –9 %. They were inconsistent and partly contrary to results published earlier. Therefore, and because the number of two contributors was too low for any statistical evaluation, further consideration of these findings related to non-grain-oriented products was abandoned. However, in the case of grain-oriented material, the simpler sample preparation, wider applicability and a measurement result that is closer to an imagined true value are the impetus for the great interest in the Epstein-SST relationship, or, very recently, in the intention of introducing SST reference values for the grading of grain-oriented materials.

Correspondingly, six manufacturers have contributed δP_{SE} results measured on 5 or more samples for some of the following grades of their grain-oriented products: M90-23P, M100-27P, M103-27P, M105-30P (2x), M130-27P, M110-23S, M120-23S, M120-27S, M130-27S, M130-30S, M140-30S (2x), M150-35S, M155-35S. Figure 2 shows the resulting relative difference $\delta P_{SE} = 100 \cdot (P_{SST} - P_{EP}) / P_{EP}$, averaged for each manufacturer and grade, determined by the 6 contributors, as circles [6]. The different colours of the fillings are assigned to the different contributors. The continuous curve represents the least square fit to the measurement results achieved for 240 of the related grain-oriented Epstein-SST sample pairs (almost all of S-type, a few of P-type material) [3] which is quoted as the informative conversion factor in Annex C (informative) of IEC 60404-3:1992/IEC 60404-3:1992/AMD1:2002 [2].



NOTE The circles are the data from 6 industry laboratories on 13 g.-o. grades (colours assigned to manufacturers). The blue continuous curve is δP representing the least square fit to the older PTB measurements [3] quoted as the informative conversion factor in IEC 60404-3 [2] (the uncertainty of the curve is characterized by a relative standard deviation of about $\sigma_1 = 2$ %[3].

Figure 2 – Relative difference $\delta P_{SE} = 100\ (P_{SST} - P_{EP}) / P_{EP}$ versus peak magnetic polarization J measured by six contributors on samples of their own products

The discussion of these findings within IEC TC 68 considered these results as unsatisfactory with regard to the purpose of introducing SST reference values for the grading of grain-oriented material. In the course of this discussion, experts from steel manufacturing industry [5] opened a new view on the Epstein-SST problem by pointing to the deceptive role of the assessment of Epstein results as seemingly absolute reference values, based on arguments given in 4.2. Moreover, whilst in general the dispersion of Epstein and SST loss values are similar, the Epstein method shows a larger dispersion than the SST method when applied to high-permeability material at the key magnetic polarization 1,7 T (see σ-values in Figure 15 a) and b)). As a consequence, the realization of a thorough comparison of measurements on grain-oriented SST sheet samples including high permeability and domain refined material according to IEC 60404-3 and its evaluation independent of Epstein measurements was proposed. Epstein measurements were to be executed in parallel in order to achieve a parallel assessment of the two dispersion characteristics.