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A method for determining the local magnetic induction near the cut edge of the ferromagnetic strip

Z. Gmyrek

Lodz University of Technology, Institute of Mechatronics and Information Systems, 90924 Lodz, Poland

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ABSTRACT

The paper deals with the problem of precise determination of the local magnetic induction. The author proposes a new way of doing the measurements using the classical needle probe method. The proceeding algorithm combined with the proposed approximation of the ΔU voltage drop, contributes to a significant increase in the accuracy of the determination of the magnetic induction distribution in the zone near the cut edge.

1. Introduction

Scientific research studies on changes in magnetic material properties resulting from mechanical or laser cutting have been conducted for many years. Both laser cutting and mechanical punching are the reason for grain structure deterioration and for the occurrence of internal stresses inside material structure. Then they are also the cause of changes in the material's magnetic properties. The literature has descriptions of the three main methods of testing local material properties that are effective in this case. The first method, called the needle probe method, allows to measure local material properties by registering the voltage measured on the specimen's surface [1]. The second method involves measuring the material's microhardness [2]. The third method, which has been used for many years, is one that uses coils placed in holes drilled near the cut edge [3]. New solutions should also be mentioned, such as those which use magnetovision cameras [4] and IR cameras [5]. This paper presents a new concept of the procedure that allows for efficient use of the needle probe method in the study of local induction values, with particular emphasis on the damaged zone as a result of the mechanical cutting process. The results of the numerical calculations performed using this concept were compared with the measurement results.

2. Basic principles and limitations of the needle probe method

The basic principles of measurements done with the needle probe method allowing for induction calculation inside the indicated ferromagnetic material were developed in the 1950s. However, for many years, due to the small value of the measured voltage signals, the method could not be used effectively – see Fig. 1.

By applying Faraday's law we can write

$$\oint_C \vec{E}\cdot d\vec{L} = -\int_S \frac{\partial \vec{B}}{\partial t}\cdot d\vec{S} \tag{1}$$

where $\vec{E}$ is the electric field intensity vector, C is a closed integration path, $\vec{B}$ is the magnetic induction vector, and S is the area enclosed by the path C.

Assuming that the magnetic induction vector has only a Y component, the vector of the induced current will have only the X and Z components. As shown in Fig. 1, voltages V_{12} and V_{34} will depend only on the X component of the electric field intensity. Similarly, voltages between points 1–4 and 2–3 will depend only on the Z component of the electric field intensity. We assume that the C integration path as presented in formula (1) represents the path passing through points 12341. Since it is impossible to directly measure the voltage between points 1–4 and 2–3, it is thus often assumed that these voltages are equal to 0 or are negligibly small as compared to the V_{12} and V_{34} voltages. Then, instead of Eq. (1), we should write its simplified form

$$V_{12} + V_{34} = -\int_S \frac{\partial \vec{B}}{\partial t}\cdot d\vec{S} \tag{2}$$

Omission of the leakage flux and adopting this assumption results in method error. This error is particularly important in the

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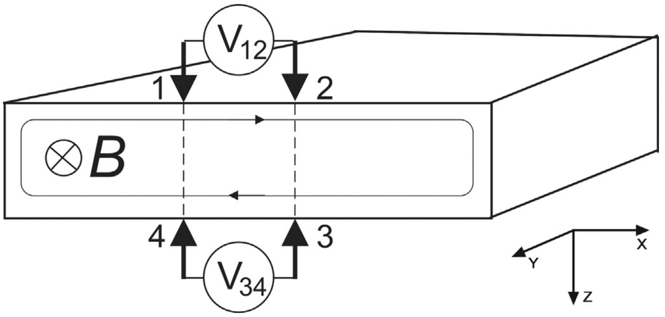

Fig. 1. The concept of the measurement in the needle probe method.

case of measurements performed in the area close to the edge. In the case of the mechanically cut edge, destruction of the material structure and the consequent change in the material properties, causes currents to flow along the *Z* axis (the transverse currents flow e.g. between points 1–4), and these, are important, even at a relatively large distance from the cut edge. In the case of a ferromagnetic strip without the damaged structure, the transverse current disappears rapidly with a distance from the edge, and may be omitted during calculation. The literature describes modifications of the set-up for the needle probe method with respect to the measurement concept as indicated in Fig. 1. but they often use more than two measuring points [1,6]. In practice, omission of the transverse currents (voltages V_{14} or V_{23}) may be accepted only in a relatively large distance from the cut edge, i.e. greater than a few mm. This paper proposes a new solution that will allow estimation of the voltage drop between points 1–4 and 2–3.

3. Description of the model used

As input to the numerical calculations, representing the properties of the damaged area, the magnetic induction's distributions as published by Peksoz [3] were used. Peksoz developed these based on measurements of the voltage induced in the coils placed in the holes drilled at different distances from the cut edge (the measurements were applied to strips those were mechanically cut). The available approximations apply to the following types of ferromagnetic strip: M250, M400, M800 and M940. All test sheets had a thickness of 0.5 mm. An example of an approximation is shown in Fig. 2. It should be emphasised that the adopted distributions are very close to those presented by Moses [7]. To verify the effectiveness of the proposed algorithm as compared to the classical needle probe method described in the literature, the author built a 3D model of the ferromagnetic strip's part by taking the damaged area into account – Fig. 3. The area damaged by mechanical cutting was divided into elementary sub-areas which used adopted the magnetic permeability that was determined based on the magnetic induction's approximation as given by Peksoz. Electrical resistivity of the tested strips were selected according to the catalogue: M250–59 μΩ cm, M400–42 μΩ cm, M800–23 μΩ cm and M940–18 μΩ cm, and assigned to both damaged and undamaged material.

The effectiveness of the proposed algorithm was tested on the aforementioned four types of ferromagnetic strip with commonly used thicknesses of 0.35, 0.5 and 0.65 mm. The numerical model built here reproduces part of the strip having the following dimensions: thickness 0.35, 0.5 or 0.65 mm (measured along the *Z* axis), width 20 mm (measured along the *X* axis), and height 0.2 mm (measured along the *Y* axis). On the upper and lower surfaces of the FEM model (*XZ* plane), the author assumed symmetry conditions enabling the modeling of a small portion of the strip. A small height of model and accepted the symmetry conditions may suggest that instead of a 3D model, is sufficient to build a 2D model. Unfortunately, in the 2D model is not possible to model the conditions in which the magnetic flux flows parallel to the cut edge and at the same time we have the knowledge of the two components of the induced current. The choice of the height of the model is dictated solely by the concern for the appropriate size ratio of elements. In the model around the strip there is a coil located within a distance of 0.4 mm. Accurate modeling of the damaged area required that it had to be divided into 45 subdivisions of the following lengths (measured along the *X*-axis): 0.05 mm (20 subdivisions), 0.1 mm (20 subdivisions) and 0.2 mm (5 subdivisions). This way the author could very carefully model the area of the material lying at a distance of 4 mm from the cut edge. The remaining part of the model, representing the undamaged material, was divided into sub-areas with a width of 0.25 mm and 0.5 mm. A fragment of the model together with the selected elementary subdivisions is shown in Fig. 3. The built FEM model contains 80 000 elements, of which about 25 000 occurred in the area of the damaged zone. The choice of mentioned number of elements has been dictated by the desire for reaching of good accuracy of the calculations of the electric field intensity waveforms, both on the surface and inside the model. Increase the number of elements over 80,000, only resulted in an increase of computation time without a significant improvement in accuracy. The numerical calculations were performed using OPERA 3D professional software. Assuming a frequency of 50 Hz, the author solved the AC steady state problem. During "tuning" of the model, calculations were performed assuming linear and non-linear magnetic material. From the point of view of the calculation (determining the voltage drop measured along a specified path), the results obtained for both types of material were very close to one another. For this reason, constant magnetic permeability was accepted for further calculations in the elementary sub-areas. In each sub-area the author assumed specified magnetic permeability determined by using the local slope of the magnetic characteristic. Since the magnetic field strength on the surface of the specimen is uniform (no matter whether it is damaged or undamaged area), so locally reducing of magnetic induction leads to a reduction of the local value of the magnetic permeability. The

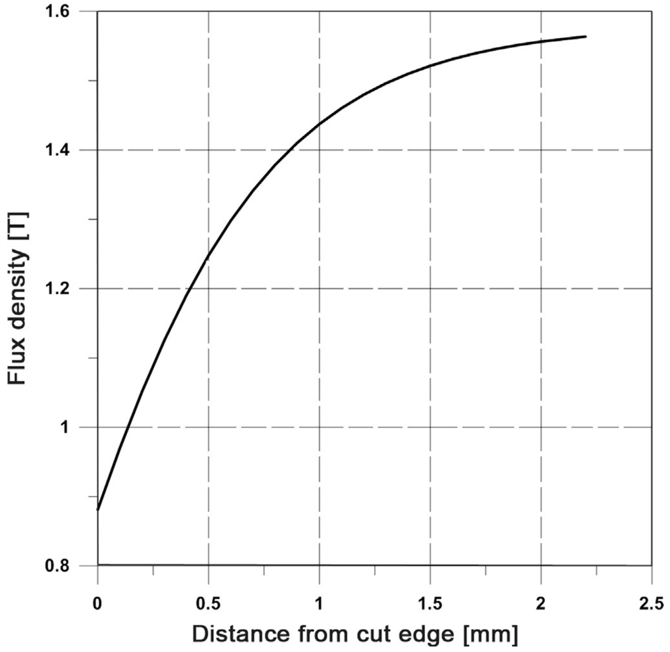

Fig. 2. Approximation of the distribution of the magnetic induction in the cut zone (material M-400) [3].