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Dynamic diagnostics of ferromagnetic materials on the basis of the phenomenon of voltage transformation

***Abstract**. Continuous production process requires continuous monitoring of the quality of material produced. The high speed of the controlled product requires a specific approach to the diagnosis of the material. The article is a continuation of the discussion of the authors on this problem. The main goal of the article is the quality control of the ferromagnetic material used as a ferromagnetic core in the quality sensor. The article presents the control system with a transformer as a sensor and a controlled material as a core. In addition an analysis of the impact of the losses generated by the eddy current on the forces and torques has been performed. The calculations have been accomplished in ANSYS environment using the finite element method and Maxwell stress tensor.*

***Streszczenie.** Ciągłe procesy produkcyjne materiałów wymagają ciągłej kontroli jakości produkowanego produktu. Duża prędkość produkowanego produktu narzuca specyficzne metody diagnostyki. Artykuł jest kontynuacją rozważań autorów dotyczącą powyższego problemu. Przedmiotem artykułu jest kontrola jakości produkowanego ferromagnetycznego materiału użytego w sensorze jakości jako rdzeń ferromagnetyczny. W artykule przedstawiono symulację układu kontroli z sensorem w postaci transformatora gdzie rdzeniem jest produkowany materiał ferromagnetyczny. Dodatkowo przeanalizowano wpływ strat powstających w produkowanym materiale na generowane siły i momenty oddziałujące na sensor. Obliczeń dokonano z wykorzystaniem środowiska ANSYS wykorzystującego metodę elementów skończonych oraz tensorów Maxwella (**Dynamiczna diagnostyka materiałów ferromagnetycznych w oparciu o zjawisko transformacji napięcia**).*

Keywords: eddy current, sensor, quality, dynamic diagnostics.
Słowa kluczowe: prąd wirowy, czujnik, jakość, diagnostyka dynamiczna.

Introduction

The article is a continuation of the work of the authors concerning the dynamic diagnostics of materials. Ferromagnetic materials produced in a continuous process are difficult to quality control during the manufacturing process. Difficulties arise from the continuous movement of the material and hence the lack of the possibility of determining the conditions of measurement [6]. The methods used for static measurements does not allow for their use in conditions of dynamic movement of the material. In laboratory instruments that allow such research specially prepared samples are most commonly used. Diagnostic methods usually help in the detection of mechanical defects in materials. It has to do with the change of the magnetic properties of the material (air gap as a defect in the material), but does not cover the entire area of material defects that may occur during the manufacturing process of the magnetic material (for example, change of magnetic properties of the solid volume when changing the ratio of iron - silicon alloy). There are also other reasons for which this type of control is extremely convenient. Production of wire or sheet requires winding on the drums which allows an easier transport and storage. Winding, however, is a process which conceals material defects (defective sections of the material are covered by successive layers of coils).

The defects of the material can be found after unrolling and testing. The aim of the work of the authors is to study and record the information in correlation with location of the defective material in the package. Previous work concerned a study of the properties of the material based on a sensor constructed from a permanent magnet. In [4], non-destructive methods of assessing the quality of the material using the flow of the magnetic flux along the test material have been discussed.

In this article the authors try to find a method of indirect measurement of material quality in the manufacturing process. The measurement of the magnetic properties is realized based on the AC current sensors and specifically on the properties of the transformation of AC voltage and further, on its basis to assess the quality of the material.

The measuring principle

Position of dynamic measurement of material quality in continuous production has been shown in fig 1. The sensor can be placed just before the winded material.

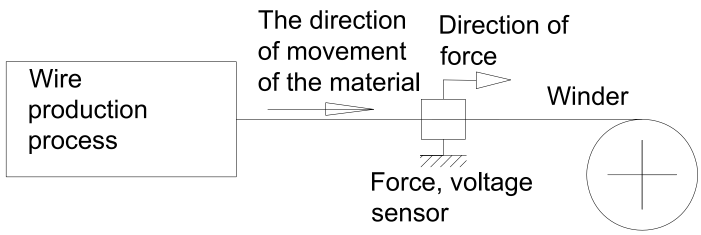

Fig. 1. Place of the sensor in a wire production scheme.

Produced wire moves in the direction of the winder and passes through the AC sensor probe (fig. 2). Position of defective material can be saved and correlated with the position thereof relative to the beginning of the wound material. At a further production stage the position of defective material can be identified based on its distance from the origin of the produced material. Identified in this way, the defective material can be easily removed.

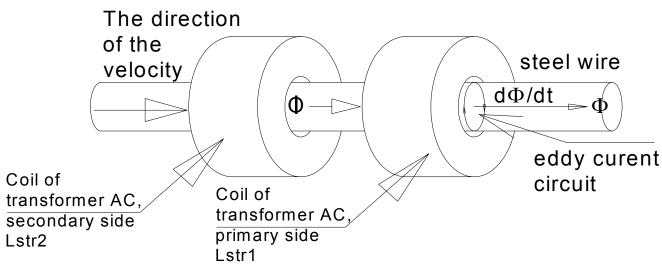

Fig.2 The principle of operation of the force and voltage sensor

When disruption of uniformity in the form of an air gap as in fig.3 or diamagnetic material is observed in the test material a disruption of the size of the force or voltage should appear.

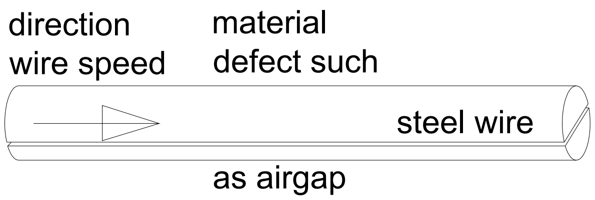

Fig.3 Example of distortion of homogeneity of the material e.g. air gap.

The sensor is built on the principle of a transformer. It has two windings: a primary and a secondary and a magnetic circuit which is made of produced wire. During the production process defected material may appear. Deformation of the material moves towards the winder. Defective material passes through the sensor. Whether it is an air gap or change in the structure of the material (change in the properties of the alloy from which the material was made) will affect the shape of the stream and the properties of the so constructed transformer. Depending on the size or shape defects should deform energy transformation in the transformer.
The stream is directed along the core-wire. Disturbances in the structure of the material should interact with the secondary coil of the transformer [9].

The method of calculating

The article provides a simulation based on ANSYS environment using Finite Elements Method and Stress Tensor Maxwell. The impact forces in a simulated arrangement have been made with using the Transient block. This allows for consideration of inhomogeneous material movement.

Computing methodology

All simulations have been performed with the Ansys program. This piece of software uses the Maxwell Stress Tensors (MST) methodology [2]. Zero boundary conditions have been assigned around the machine. The area around the proces area has been divided into 300.000 triangle elements. The elements have different dimensions, depending on the importance of the considered area. The sensitive space around the air gap, sharp shapes around the poles, was analyzed with finer mesh. Software used in simulation makes it possible to model both: moving and non-moving elements. The proces area has been divided onto the stator with six winding poles as a non-moving part of the motor, and the rotor with six poles magnetized by permanent magnet elements as a moving element. The shape of the air gap between the space of sensor is very important. The rotor axis is placed perpendicularly to the surface showed in Fig. 4. Considering the formulas for computing force:

(1) $$F = \int \left[\frac{1}{\mu_0} B(B \cdot n) - \frac{1}{2\mu_0} B^2 \cdot n \right] dC$$

and torque

(2) $$T = r \cdot F$$

Values in formulas (1) and (2) are as follows: B - momentary value of induction in the air gap B [T], N - unit vector, perpendicular to the surface of rotor, μ_0- magnetic permeability of vacuum μ_0= 4 $\pi \cdot 10^7$ [H/m].

Value of torque is calculated from the formula (3) taking the radius of rotor as r [m]. It is important to assume a very big difference between magnetic permeability (minimum 1/1000) in those two analyzed spaces (air and iron). In the calculations the normal part of flux vectors in the air gap, and big difference of magnetic permeability between the air and electromagnetic steel were assumed. The presence of the air gap in the analyzed region fulfills these conditions.

Assumptions for the calculation

All simulations for the calculation of flux density, forces, and torques have been performed by the program Ansys. An object shown in fig. 4 has been taken for the calculations. The movement area of the produced material had to be restricted due to the applied method of analysis. The analyzed area should have a limited finite surface in view of the need to define the boundary conditions. The construction of the test model consists of a wire ring with a diameter of 3 mm formed in the shape of a circle. The rotation of the wire wheel simulates sliding (produced) material. At a certain point of the simulated production process an air gap was placed in a limited area positioned at a fixed point of the rotating wire wheel. Circle made of wire is turning around on their own axis. At the bottom there is the sensor based on AC transformer and effect of Eddy current. While moving through the sensor, the defective material should cause distortion of the field, which will lead to distortion of the signal transformed by the sensor. All details of the sensor are explained on the fig. 2. In real situation there is no ring of wire, but simply produced wire. It is the easiest way to describe in the program this kind of object.

In the Fig.3 in the middle of wire there is an air gap which symbolizes defect of material. The air gap inside of material is moving with the wire along sensor.

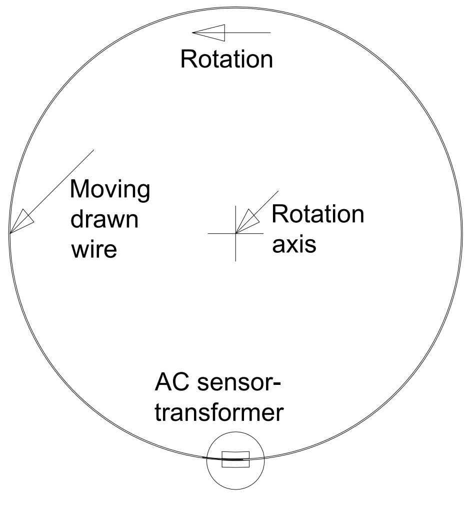

Fig. 4. Schematic process adopted for the calculation model

AC sensor works as a transformer whose core is sliding wire. In addition, the transformer magnetic field induces eddy currents effect. It is the source of the forces acting on the sensor. By measuring the voltage, current and the forces acting on the sensor can identify disturbances in the magnetic field resulting product defects.

Computational results

Diagram of sensor with use of electric power transformer is shown in Fig. 2. Electrical circuit consists of a source of sinusoidal voltage of 70V connected to the primary side of the transformer. The primary side coil Lstr1 is connected via a series resistor limiting the primary side current. The secondary side of the transformer Lstr2 is connected to a resistor loading 2,000 Ohm. The voltage drop is also the output signal of the sensor. All circuitry data was described in fig. 5. Dynamic voltage waveforms at the input and the output of the sensor are presented further on in this article. The output data is shown in the form of corresponding measurement equipment connected to the controlled circuits.

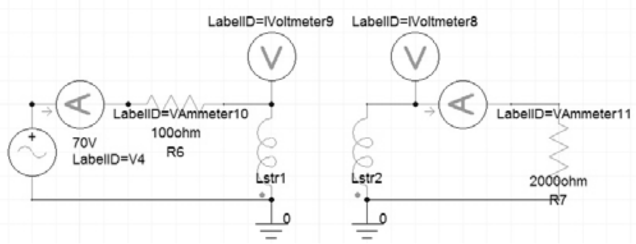

Fig. 5 Scheme of the sensor supply

Fig. 5 describes the output voltage on the secondary side of the transformer supplied with sinusoidal voltage source of 70V, 50 Hz.

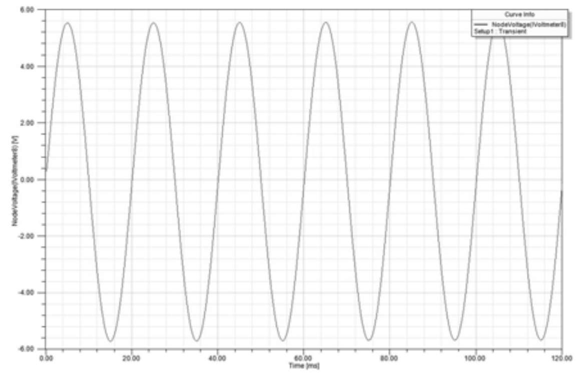

Fig. 6 Graph of voltage for secondary coil of transformer. Supply voltage for primary side of transformer 70V, 50Hz.

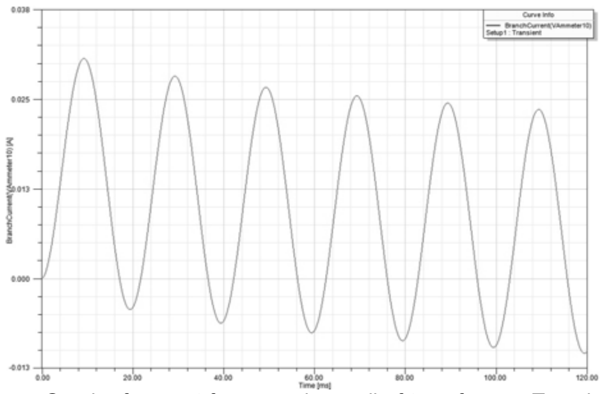

Fig. 7 Graph of current for secondary coil of transformer. Transient state.

Voltage and currect waveforms are shown in figures 6 and 7. The secondary side voltage did not change its original shape, as expected. Changes in amplitude were not studied. A significant change can be observed in the form of current. The upcoming fault (air gap sliding along the sensor) significantly changed its shape. At the timewave, it is synchronized with the air gap moving towards the sensor. It changes the magnetic properties of the material core, which, for the sensor, is the wire. Such observation, however, does not make a significant change in the output signal. The sensor signal was not satisfactory for authors of the conducted experiment. A starting point of an air gap is observed near 80ms. Looking on the shape of voltage, there is no differences between the space with and without air gap in material.

Looking at the shape of the current in the secondary winding of the transformer it is a typical shape of transient state for transformer which is not a desired property for this type of sensor. Forces and torques influencing the sensor were measured in view of the eddy currents occurring in the system.

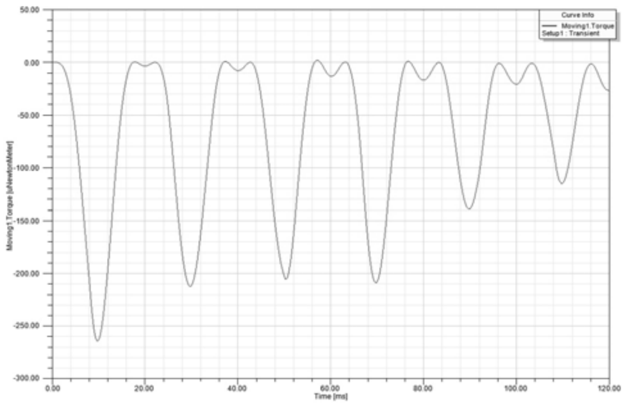

Fig. 8 Graph of torque influencing on the sensor. Starting point of air gap is at 80 ms

It was assumed in the experiment that the forces and the torques are proportional to the radius of ring of wire shown in fig. 4.

The unsatisfactory signal of the change in the shape of current and the voltage of secondary side of the sensor impelled a further research. A change in the core properties may cause a change of flux density in the sensor. A simulation investigating the size of change in the force exerted on the sensor was conducted. Through the field, the moving wire (the sensor core) affects the forces between the sensor coils and the wire. In a case simulated on the entire system model, forces are reflected in the torque acting on the sensor. The advancing wire will attempt to move the sensor in the direction of movement. The resulting torque can be measured. The torque size can be an indicator of core deformation and hence the size of defects in the moving material. In fig 8 of time versus force acting on the sensor, material defect can be clearly observed which proves the suitability of that kind of sensor in quality testing.

Proportion between the air gap (0.1 mm) and section of the core (3 mm) in the experiment is 3.3% of the core surface.

At the same time a change of the amplitude is 36.4%. The observed change is significant and indicates a change in the material reinforcement of over 10 times. A significant improvement of the AC current sensor comparing to the constant filed sensor described in [5] has been observed.The forces acting on the magnets are recalculated from the torque To. Diameter for the ring of wire is equal 1m. The speed of rotation is 180 ° /s. For the above settings the torque is To = 220 Nm between points of "start" and "stop". It is an area of uniform segment of the wire.The rest of wire is a material with a modelled defect of a 100 μm thick air-gap. Computed torque for that area is T=140 Nm. Difference is 80 Nm which is 36,4 % of total torque. All information were shown in tab. 1.

Table 1. Comparison of the simulations results

Simulated material	Torque [Nm}
Uniform material	220
Material with defect	140
Difference	80

Conclusions

Diagnosis of the defective region in a continuous production process of the materials is a difficult and timely problem. Non-destructive testing [10] enables diagnostics in production processes. The test material is moved only in the vicinity of the sensor. The condition is necessary due to the lack of sampling for quality testing during the manufacturing process. Pressure on high volume production requires rapid methods. Elimination of free and not very accurate observational methods (eg. magnetic powders) [8,7] leads to the search for sensors in the area of electric and magnetic solutions. The study of the deformed magnetic field [4] is one of the ways to improve the quality of this kind of research and to increase its speed. Diagnostic sensors, whose construction is based on the interaction of the magnetic field prefer a diagnosis of ferromagnetic or conductive materials. In addition, the study of magnetic materials produced as a wire or tape (sheet) enables simultaneous control of these materials in the manufacturing processes. The method of winding the produced material on a drum with a view to easy storage impairs, to a large extent, the selection and rejection of the defective material. After being wound on a drum or reel, the defective material disappears under the layer of material produced. Dynamic diagnosis enables simultaneous testing and notation of the position of the defective material. Remembering the distance between the beginning of the wire or sheet and the defective section of the material makes it possible to identify and discard the defective section during the process of undwinding. The study confirmed that deformation of the material uniformity, i.e. defective material, accentuated most when checking the force acting on the sensor during its testing. Dynamic changes in the torgue-force size in the observed object are shown in the timewave presented in fig. 8. The use of force sensor as an intermediate sensor of the defective material does not reduce the speed of measurement (strain gauge measurement). As the forces compared in Tab. 1 show, it improves the measurement accuracy. In the simulation, a torque was used as an indicator, according to equation (3). In reality, a force sensor can be constructed either by measuring the torque or force. The article is an attempt to solve the problem with a sensor constructed based on the operation of the transformer. The expected change of the shape of voltage waveform did not give satisfactory results. The observations of the forces generated by eddy currents give scope for further analysis.

Correlation of the ferromagnetic materials and real measurements in a system will allow the clarification of dependency between defect in materials and shape of wave forms for electrical signals.

Measurements proposed in the article can be an effective method of the diagnosis of the defects in ferromagnetic materials in a dynamic state. Practical application requires a detailed analysis of the relationship between changes in the size of the forces and the mechanical properties of the materials.

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