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Dynamic diagnosis of conductive materials on the basis of force acting on the sensor made of permanent magnet

***Abstract**. Checking the quality of the material during the manufacturing process causes problems. The impact of motion in conjunction with the magnetic field induces eddy currents and forces. They affect the field source element through the dynamic forces occurring in the process of movement. The value of the impact force may indicate material defects arising during the manufacturing process. The use of this phenomenon may assist in the quality control of the produced materials. The paper presents the simulation of such a phenomenon and calculations of the forces and torques occurring in this type of process. The calculations were accomplished in ANSYS environment using the Finite Element Method and Maxwell Stress Tensors Method.*

***Streszczenie.** Sprawdzanie jakości drutu, blachy w czasie procesu wytwarzania sprawia problemy. Oddziaływanie dynamiczne ruchu w powiązaniu z polem magnetycznym wywołuje efekt prądów wirowych oraz sił. Wielkość siły oddziaływania może wskazywać na wady materiału pojawiające się w czasie procesu produkcji. Wykorzystanie tego zjawiska może pomagać w procesie kontroli jakości materiału. W pracy przedstawiono symulację takiego procesu oraz dokonano obliczeń sił i momentów występujących przy tego rodzaju procesie. Obliczeń dokonano w oparciu o środowisko ANSYS z wykorzystaniem metody elementów skończonych oraz tensorów naprężeń Maxwella.(**Dynamiczna diagnostyka materiałów ferromagnetycznych w oparciu o siły oddziaływujące na sensor z magnesu stałego**).*

Keywords: eddy current, sensor, quality, dynamic.
Słowa kluczowe: prąd wirowy, czujnik, jakość, dynamika

Introduction

Continuous production processes of many materials require continuous quality control [4, 5, 6]. Production of steel wire or sheet without current quality control could result in defective material wrapping onto the spool output. There are many methods to control the production of ferromagnetic materials in a static state. Samples can be accurately checked. However, it is impossible to detect defective material without scrolling and notching of the sample from a reel [7]. The authors are trying to find a method of indirect measurement of material quality during the manufacturing or exploitation process [7, 8]. The dynamic measurement of magnetic properties and rating the quality of the produced material on its basis is highly difficult.

The measuring principle

Fig. 1 shows the scheme of the location of dynamic measurement of material in continuous production of wire or sheet steel. The sensor is placed just before the winding of the produced material, for example: spool of steel wire - winder.

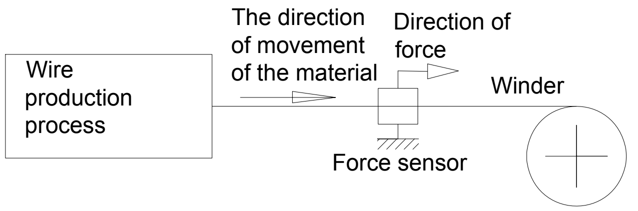

Fig. 1. Location of the sensor in a simplified schematic wire production.

In Fig. 2 produced wire moves in the direction of the winder. The wire passes through the sensor probe.

Movement of wire induces the rise of force acting on the permanent magnet. This is the result of eddy currents effect on the magnetic field of the magnet. Eddies current circuit is marked as a ring located inside the wire in figure 2. Induced eddy current generates a magnetic field opposing the wire movement, and so it works as a force on a permanent magnet. Movement generates a force that acts on the permanent magnet in the direction of a moving wire. This is due to the impact of eddy currents in the magnetic field of the magnet. The movement of the wire is also a source of the energy needed to produce the forces interacting on the permanent magnet.

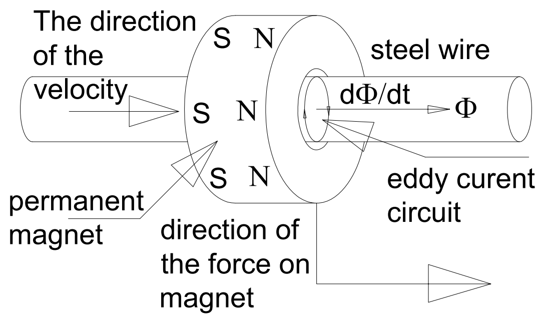

Fig.2 The principle of operation of the force sensor

A disruption of uniformity in the form of an air gap or diamagnetic material occurring in the tested material will result in disruption of the value of the force as in Fig. 3.

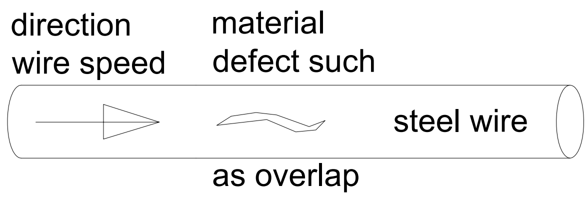

Fig.3 Example of distortion of homogeneity of the material e.g. air gap.

The method of calculating

Simulation in the present paper was calculated in ANSYS Maxwell environment. The impact forces in simulated conditions have been prepared using the Transient block allowing analysing the environment with the inhomogeneous material movement.

Computing methodology

All simulations have been performed with the Ansys Maxwell program. This piece of software uses the Maxwell

Stress Tensors (MST) methodology [3]. Zero boundary conditions have been assigned around the machine. The area around the motor 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 inside the permanent magnet sensor, 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 object has been divided as a moving and non-moving part of the object, and the sensor magnetized by permanent magnet elements as a non-moving element. The shape of the air gap inside the sensor is very important. The object axis is placed perpendicularly to the surface showed in Fig. 4. Considering the formulas for computing force:

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

and torque

$$T = r \cdot F \tag{2}$$

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 $\mu_0 = 4\ \pi \cdot 10^7$ [H/m].
Value of torque is calculated from the formula (2) 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 ANSYS Maxwell program. An object taken for the calculations has been shown in fig. 4. Circle made of wire is turning around on its own axis. There is the sensor based on the eddy currents effect at the bottom of the wire circle. All the details of the sensor are explained in fig. 5. The ring of wire has been used to model a real process of the wire production line. It is the easiest way to model in the program this kind of object.

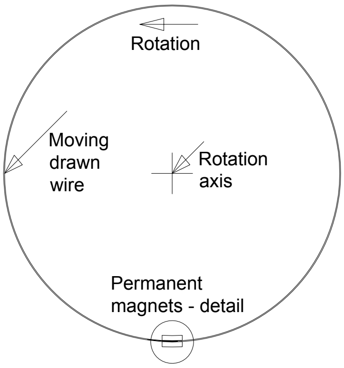

Fig. 4. Schematic adopted for the calculation model

In the middle of the wire there is an air gap which symbolizes a defect of material. The air gap inside of material is moving with the wire along sensor made of permanent magnet. Movement and magnetic field induce the flow of eddy currents which further influences the sensor increasing the measured force. Measuring this force allows to conclude about a disruption magnetic field and to detect defect of wire.

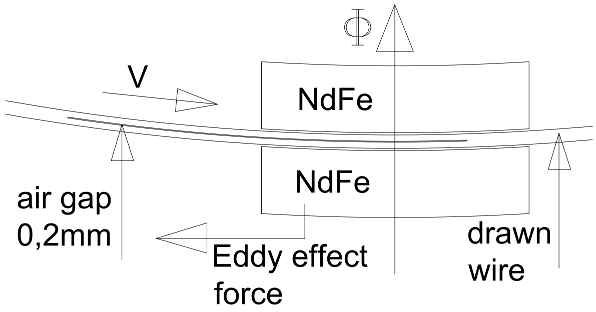

Fig. 5. Details of the scheme of Fig. 4 used for calculation

Computational results

Fig. 5 describes the air gap as a drawback (disruption) in the internal structure of the wire. The effect of such disturbances on the force acting on the sensor was calculated and shown in Fig. 6.

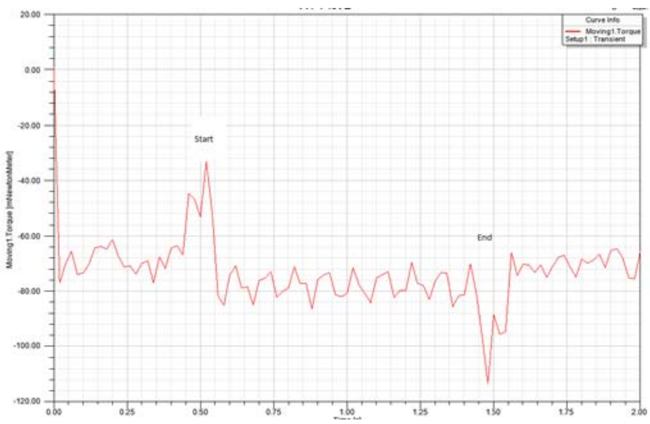

Fig. 6. Dependence of the torque from an angle of circle rotation . The simulated defect of the wire is located between the peaks on the diagram (Start-End).

It is assumed in the experiment that the forces are proportional to the torque for the ring of wire. The same effect can be observed by considering the impact of the wire rectilinear moved in a horizontal direction. In experiment thickness of wire was assumed as 3mm. Thickness of air gap inside material: 20 μm. This represents 6.6% of the entire cross section of the wire.
The forces acting on the magnets are recalculated from the torque T_0. Diameter for the ring of wire is equal 1m. The speed of rotation is 180 ° /s. In that situation the torque is T_0 = 77,65Nm between points of "start" and "end". It is an area of uniform segment of wire. The rest of wire has the defect as the air-gap with thickness 20 μm. Computed torque is T_{01} =69,55 Nm with a difference of 8,1 Nm which is 10 % of total torque. All information was shown in tab. 1.

Table 1. Comparison of the simulations results

Air-gap 20μm	Cogging Torque
Uniform material [Nm]	**77,65**
Material with defect [Nm]	**69,55**
Difference [Nm]	**8,1**

In the other case in the fig. 7 is shown an air-gap which is significantly shorter than on fig. 4. The influence on the sensor is different. Important in this experience is that the air-gap is shorter than length of sensor. Interesting is, or this length is disturbing for process of detection for defect in material.

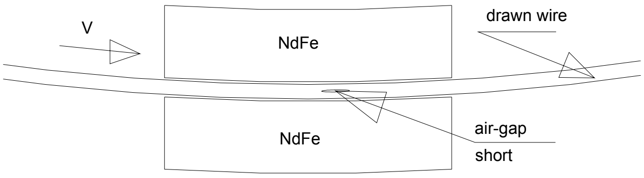

Fig. 7 Details of the scheme of Fig. 4 used for calculation with short air-gap

Results of simulation are shown in fig. 8.

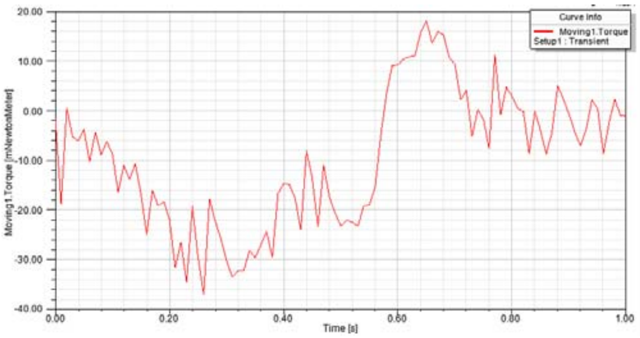

Fig. 8 Dependence of the torque from an angle of circle rotation for very short air-gap in the wire as in fig. 7

The speed of rotation is 10 °/s. The rest of parameters are the same as for first case. Looking on fig. 8 it is possible to observe that influence on the torque is different. Dependency forces and torques from the speed of rotation affect on the results of measurement. When the size of force is addicted to speed of movement, it is possible survey with real results.

Conclusion

Measuring the force affecting moving material in a magnetic field can be an effective way of diagnosing defects in ferromagnetic materials in dynamic condition. Practical application requires a detailed analysis dependency between changes of the forces magnitude and mechanical properties of the material. In the modelled materials, the 20 μm air-gap results in a measurable reaction in the system. It is yet to determine whether similar gaps have a major influence on the quality and durability of the produced materials regarding its mechanical properties. The limits of accuracy, the impact of changes of speed, location of the wire in the area of measurement are the areas for further research. Demonstrating the usefulness of the method of measuring the force with dynamic process of diagnosis of the conductive materials (this method due to the "Eddy Effect current" allows testing various conductive materials) will require a detailed study of this phenomenon in real conditions and confronting the results with the results of mechanical properties tests and mechanical endurance.

Further research the links between different kinds of materials, value of forces, type of defects in materials and also dependencies between positions researched materials into magnetic sensor and what is perhaps the most important dependency between speed of movement for tested materials and speed of sensor reaction can be the field of work for authors in the future.

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