Arch. Min. Sci. **63** (2018), 1, 221-227

Electronic version (in color) of this paper is available: http://mining.archives.pl

DOI 10.24425/118896

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APPLICATIONS OF MAGNETOMETRIC SENSORS BASED ON AMORPHOUS MATERIALS IN DIAGNOSTICS OF WIRE ROPES

MATERIAŁY AMORFICZNE W PASYWNEJ METODZIE BADAŃ LIN STALOWYCH EKSPLOATOWANYCH W SZYBACH GÓRNICZYCH

The study explores potential applications of magnetometric sensors based on amorphous materials in diagnostics of wire ropes without external magnetic fields. Ready availability of magneto-impedance technology makes it suitable for innovative sensor applications, to register magnetic anomalies arising in wire ropes. These anomalies are associated with wire deformations and cracking, including cracks which do no generate air gaps encountered in compact ropes widely operated in hoisting installations in mines.

Keywords: magnetic inspection of wire ropes, diagnostics, magnetometric sensors

W artykule przedstawiono nowe możliwości wykorzystania, zbudowanych na bazie materiałów amorficznych, czujników magnetometrycznych w diagnostyce lin stalowych bez zastosowania zewnętrznego pola magnetycznego. Dostępność czujników magneto impedancyjnych pozwala na budowę innowacyjnych czujników pomiarowych pozwalających na rejestrowanie anomalii magnetycznych jakie pojawiają się w linach stalowych. Dotyczy to anomalii związanych z występowaniem deformacji i pęknięć drutów w tym nie generujących szczelin powietrznych z jakimi mamy do czynienia w linach kompaktowanych stosowanych powszechnie w górniczych urządzeniach szybowych.

Słowa kluczowe: badania magnetyczne lin stalowych, diagnostyka, czujniki magnetometryczne

1. Introduction

Amorphous materials are alloys that have disordered atomic-scale structure, their molecules in a rather chaotic arrangement instead of crystalline structure characteristic of most metals (Fig. 1). Typically those alloys have good elasticity and mechanical strength, which seems to

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be a rare combination. Their mechanical strength is nearly three times higher that of a majority of metals. When heated, they can be easily worked because they are highly plastic, similar to chewing gum (Dobrzański, 2006).

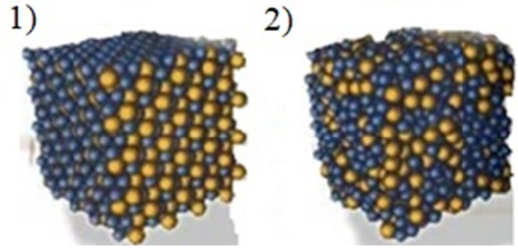


Fig. 1. Structure types 1) crystalline structure 2) amorphous structure (Dobrzański, 2006)

An amorphous phase rarely occupies the entire volume of a real substance, in most cases it co-exists with the crystalline phase. Amorphous structures do not exhibit grain boundaries, dislocations, heterogeneity or other defects characteristic of crystalline substances, instead there are domains of crystalline phase intermixed with amorphous phase domains.

New advances in modelling and applications of magnetic materials in magnetic circuit components further the research work in the field of materials and electrical engineering. It is difficult to pinpoint those areas of engineering expertise which do not make use of magnetic materials, that also applies to the active MTR method (magnetic testing of wire ropes) which relies on external magnetic fields (Kwaśniewski, 2010). Passive methods of wire rope inspection utilise the magnetic fields of those structures to detect the magnetic anomalies with the use of high-sensitivity magnetic sensors, including those based on amorphous materials.

Amorphous metals are a spectacular discovery made in the late 20th century. A major advantage of amorphous wires and ribbons is their good electrical resistivity, 2-4 times greater

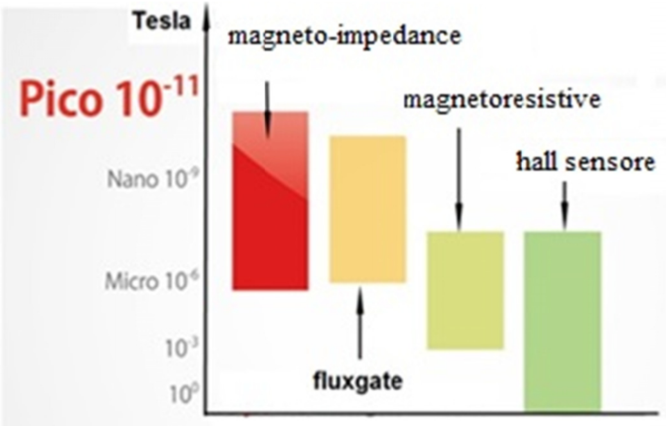


Fig. 2. Operating range of magnetic field sensors
(http://www.fujidenolo.co.jp/english/technology/mi-sensor-technology.html)

than that displayed by crystalline materials, which is of particular importance in the context of minimising losses due to eddy currents. Besides, in amorphous materials the Hall voltage level is relatively high (Wac-Włodarczyk, 2012).

Applications of magnetometric sensors based on amorphous materials have now become widespread. Cutting-edge magneto-impedance MI sensors utilising amorphous wires have three major advantages: small size, high sensitivity of the order of picotesla and the rate of signal registration of the order of GHz.

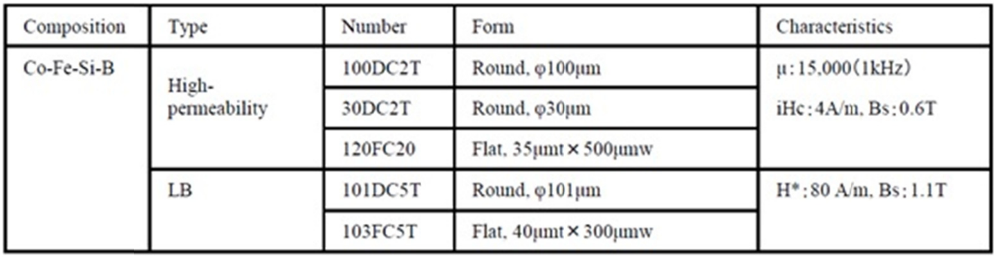
Operating ranges of various types of magnetic sensors are shown in Fig. 2.

2. Theoretical backgrounds of magneto-impedance

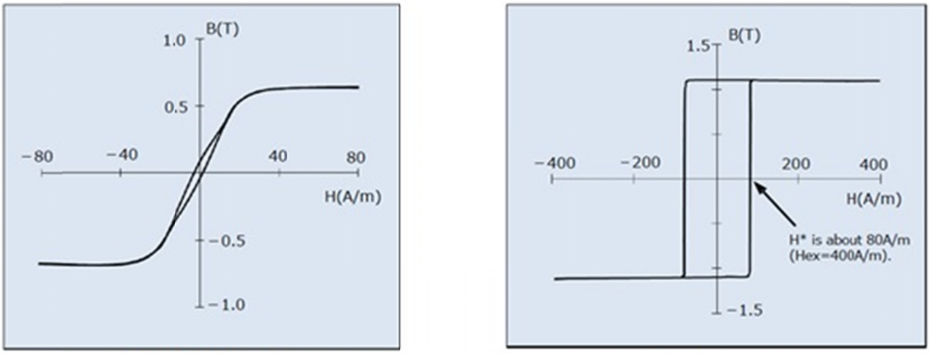
Parameters of two types of amorphous wire Co-Fe-Si-B are summarised in Table 1, their magnetic properties are given in Fig. 3.

TABLE 1

Parameters of amorphous structures (https://www.aichi-steel.co.jp/)



Composition	Type	Number	Form	Characteristics
Co-Fe-Si-B	High-permeability	100DC2T	Round, φ100μm	μ: 15,000(1kHz) iHc: 4A/m, Bs: 0.6T
		30DC2T	Round, φ30μm	
		120FC20	Flat, 35μmt × 500μmw	
	LB	101DC5T	Round, φ101μm	H*: 80 A/m, Bs: 1.1T
		103FC5T	Flat, 40μmt × 300μmw	



Hight permability

LB

Fig. 3. Hysteresis loops of amorphous wires (https://www.aichi-steel.co.jp/)

Magneto-impedance sensors based on amorphous wires utilise the skin effect whereby the current actually flows on the core surface exclusively. Fig. 4 illustrates the principle of detecting the external magnetic fields.

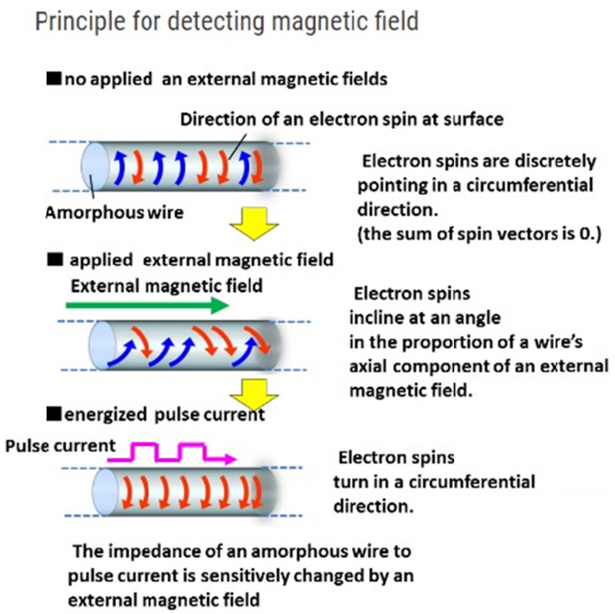


Fig. 4. Principle of external field detection in an amorphous wire
(http://www.fujidenolo.co.jp/english/technology/mi-sensor-technology.html)

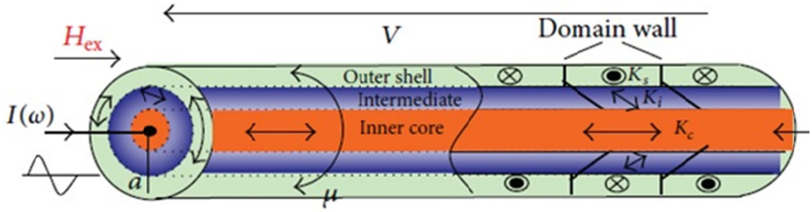


Fig. 5. Domain structure in an amorphous wire magnetised utilising the skin effect
$I(\omega)$ – varied supply current, Hex – external field strength (Mohri et al., 2015)

When the outer layer thickness (Fig. 5) in which current flows (skin depth) is much less than the wire radius, the skin effect is regarded as strong. Accordingly, impedance is given as: for: $\delta \ll a$ (strong skin effect; $\omega \gg 2\rho/\mu a^2$),

$$Z = \frac{(1+j)aR_{dc}(\omega\mu H_{ex})^{\frac{1}{2}}}{2(2\rho)^{\frac{1}{2}}} \tag{1}$$

where: ω = angular velocity of supply current, μ – peripheral maximal difference in permeability of an amorphous wire, a – wire radius, H_{ex} – external field strength, R_{dc} – wire resistance in a *dc* circuit in ohms, $R_{dc} = \rho l/\pi a2$, ρ – resistivity of amorphous wire (130 μΩcm), l – length of the core wire.

Magneto-impedance (MI) sensors utilise variations of impedance of a thin layer or a thin wire supplied with current with frequency of up to several hundred MHz. This impedance variation is associated with the change in skin depth and the change of permeability of magnetic material due to the varied external field strength. Variable output voltage is related to impedance. Fig. 6 shows an implementation of MI sensor.

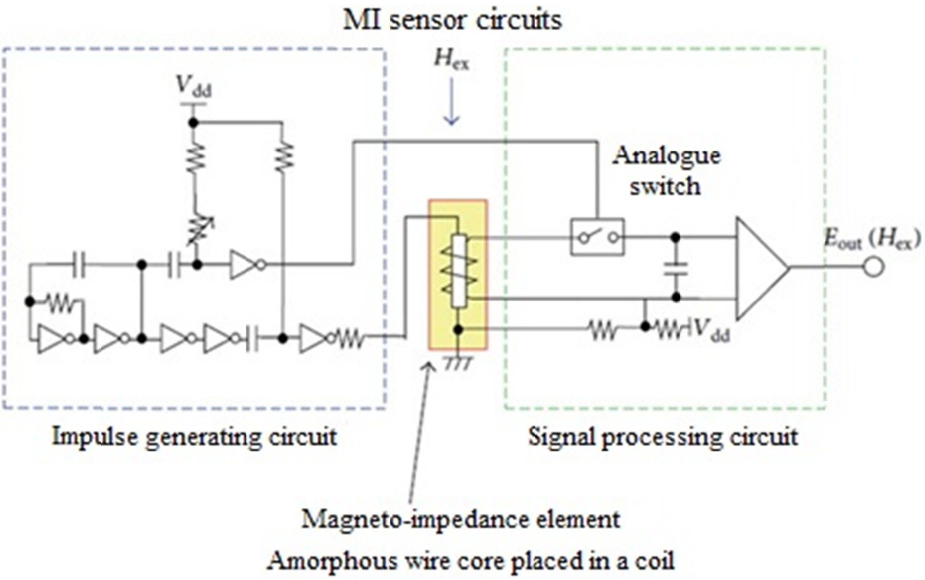


Fig. 6. Schematic diagram of a sensor with a hysteresis loop, for industrial applications (Mohri et al., 2015)

The dependence of output voltage on the external field strength is shown in Fig. 7.

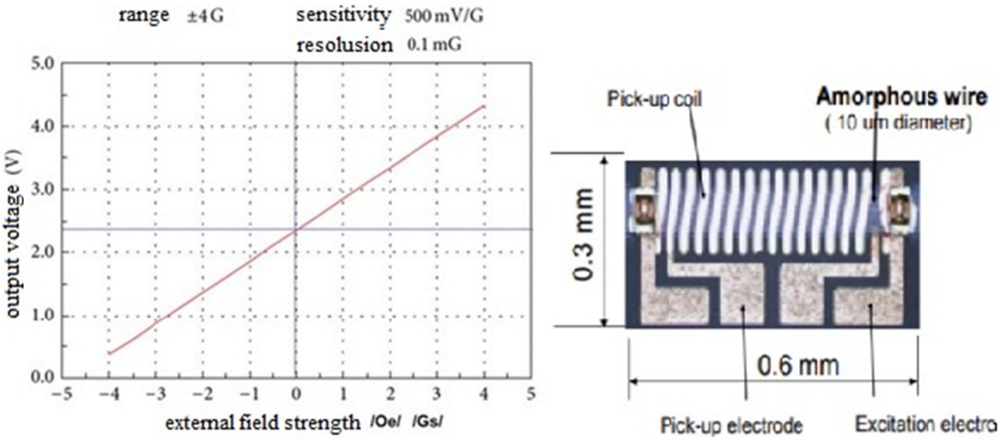


Fig. 7. Voltage vs field strength characteristic and a view of an MI sensor element (Mohri et al., 2015)

3. Practical applications of MI sensors to wire rope inspection

For a core made of amorphous material with high magneto-impedance and high current frequency (of the order of MHz), we get picotesla sensitivity. Several years ago this level of sensitivity was could be achieved only in very costly magnetic sensors SQUID and TMR. A major advantage of MI sensors is their wide operating range (up to several mili –Tesla), coinciding with that of SQUID sensors, transductor sensors used in conventional MPM method by Energodiagnostyka and EddySun Electronics companies, and huge magnetoresistive (AMR,GMR) sensors. MI sensors also encapsulate the operating range of sensors utilising the Hall effect – those designed for measurements of strong and middle-strength magnetic fields (from 500 μT to several T).

Hall sensors are widely used in MTR magnetic inspection to detect the changes in reluctance of magnetic circuits (detecting corrosion and continuous losses of the rope cross-section. The measuring bandwidth of MI sensor ranges from 0 to 1 MHz, depending on the specific requirements for the given application: scanning rate, resolution, signal-to-noise ratio SNR (Kwaśniewski et al., 2017).

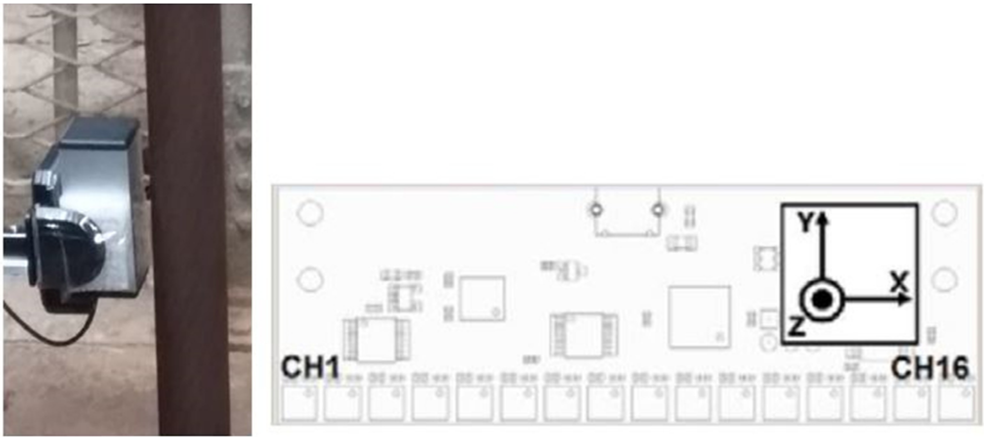


Fig. 8. Measuring head with magnetic guides (on the left). Schematic diagram of MI sensors configuration within the magnetic guide and the arrangement of measurement axes (on the right)

MPM measurements of compacted ropes (Bridon Tiger Brand Dyform 34LR, F42 mm 34(w)xk7-wsczZ B(Zn), according EN 12386-2, seven years of work, number of cycles 50000-52000) operated in the shaft Bzie 1 rely on a matrix array 2×16 of three-axis Magneto-Impedance sensors (digital compasses) arranged in the vertical line about 12 mm from the wire rope, with resolution 0.6 μT and parallel sampling (Fig. 8). Measureable range: +/–1.2 mT, linearity: 0.5% FS, simultaneous sampling: 66,6 Hz.

Thus registered magnetic field distribution allows for implementing the 3D absolute encoder (measuring the directions and velocity of the rope movements). The distance between the magnetometers and the distance between magnetic guides- 10 mm. Data transfer from the sensors to computers relied on serial transmission standard USB 2.0.

A record of measurements of a compact rope section is shown in Fig. 9. Measurements were taken with MI magnetic sensors based on a high-sensitivity amorphous wire, revealing magnetic anomalies due to rope deformation and wire cracking (in the absence of external magnetic fields).

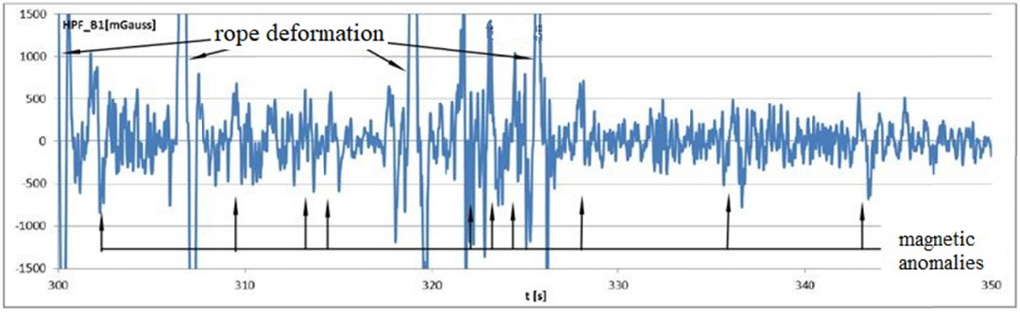


Fig. 9. Record of compact rope testing using MI sensors during the upward travel (magnetic anomalies attributable to broken wires)

4. Conclusions

Experiments were performed to demonstrate the feasibility of detecting magnetic anomalies in compact ropes by using sensors with amorphous wires implemented in MI sensors, without applying a strong magnetic field. This approach offers high sensitivity, the adequate operating range and resolution of the employed MI sensors. The investigated matrix array of magnetometers allows a reliable detection of wire cracking with no gaps, which is a prerequisite for improving the safety features of compact ropes that are now in widespread use in hoisting installation in mines.

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