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EMBEDDED DEVICES AND METHODS FOR DEVELOPMENT OF SPECIAL NON-CONTACT APPLICATIONS

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Abstract. There are applications which require particular approaches for each of the used parts. The non-contact strain sensors based on microwires with positive magnetostriction requires specific technological processes starting from casting until development of the corresponding non-contact sensor device. The developed contactless sensors can be embedded into various industry critical parts which require continuous monitoring and maintenance. Hence, specific embedded devices and specific framework should be developed to provide industry reliable solution. The paper describes the technological process of casting microwires, methods of improvement casting process and stress annealing methodology used to obtain appropriate non-contact sensible elements based on microwires. Also, the paper describes the framework of using these elements in non-contact monitoring applications of the condition of specific engineering objects/structures.

Keywords: *contactless sensing, microwire, strain sensor, collimation group/device, embedded system, edge computing device.*

Rezumat. Există aplicații care necesită abordări speciale pentru fiecare dintre părțile utilizate. Senzorii de deformare fără contact pe bază de microfir cu magnetostricție pozitivă necesită procese tehnologice specifice începând de la turnare până la dezvoltarea unui dispozitiv senzoric fără contact. Senzorii fără contact dezvoltați pot fi încorporați în diferite părți critice din industrie care necesită monitorizare și mentenanță continuă. Prin urmare, ar trebui dezvoltate dispozitive încorporate specifice și o arhitectura specifică pentru a oferi soluții de încredere pentru industrie. Lucrarea descrie procesul tehnologic de turnare a microfirelor, metode de îmbunătățire a procesului de turnare și metodologia de recoacere la stres utilizată pentru obținerea de elemente sensibile fără contact corespunzătoare pe bază de microfire. De asemenea, lucrarea descrie cadrul de utilizare a acestor elemente în aplicații de monitorizare fără contact a stării unor obiecte specifice.

Cuvinte cheie: *senzori fără contact, microfir, senzor de deformare, grup/dispozitiv de colimare, sistem încorporat, dispozitiv de calcul la margine.*

1. Introduction

It is well known that composite structures are prone to external mechanical loads and to variations in environment conditions, both of which could lead to major degradation of their mechanical conditions. Therefore, using Structural Health Monitoring (SHM) becomes paramount in a number of fields like civil engineering, aerospace industry or energy. SHM generally refers to any type of damage detection procedure. Generally speaking, SHM is the automation of the condition assessment process of an engineered system [1, 2].

To systematically monitor the condition of structures, SHM relies on a mix of technologies and methods. These are aimed at sensing, analyzing collected data and elaborating computational models able to predict the occurrence of damages. In this context, a critical challenge is in designing the sensing solution, which is a difficult task. The field implementation of sensing solutions is still in its infancy, attributable to different economic and technical issues.

There are applications in which sensible element should be integrated into monitored environment to have a better picture over the processes inside. An example of such non-contact sensor application is strain gauge based on microwires (SGM). Such sensible elements can be used in applications with contactless measurements for composite materials [3, 4]. These kinds of sensors require meticulous casting process along with other technological processing to develop a suitable sensor for special applications. Last but not least, applications can have an extraordinary impact on industry only considering the constrains of the sensors and modern Machine Learning (ML) [2, 5] approach along with latest edge computing technology [6, 7], its high scale integration into microcontrollers or cloud computing. Note that ML for SHM has become popular due to technological advances in sensors [8, 9], high-speed Internet and cloud computing.

It can be concluded that distributed embedded sensing systems as well as custom platforms need to be explored/developed in order to provide industry-specific robust and cost-effectively solutions.

2. Strain sensors based on microwires

In order to identify the manufacturing technology of strain sensors based on microwires, a technological and testing program of microwires was established. The objectives of the program were defined as:

- Researching the ordering processes of the amorphous structure under the action of temperature and the stretching processes of microwires from alloys with positive and negative magnetostriction.
- Identification of alloy composition, processing methods, with the aim of obtaining microwires with a high dependence of coercive force on external mechanical stresses.
- Research of the processed microwires, especially the characteristic of the magnetic properties depending on the applied stretching stresses.

A lot of microwires were selected for research. They can be grouped by material properties as follows:

- With positive magnetostriction: $Fe_xB_ySi_z$, $Co_wFe_xB_ySi_z$, $Co_vFe_wCr_xB_ySi_z$.
- With negative or close to 0 magnetostriction: $Co_vFe_aCr_xB_ySi_z$, $Co_aFe_bB_ySi_z$.

The size of selected microwire was 20±3; 30±3; 45±5 µm with a glass coat of 3±1; 6±1. For the selected wires the following research and measurements were targeted:

- Measurement of the actual diameters of the core and the thickness of the glass coat.
- Measurement of magnetic characteristics when adding stretching loads (pulse forms and parameters of the hysteresis loop), as well as in the temperature range of 20 - 50 ° C (preferably 20 - 100 ° C).

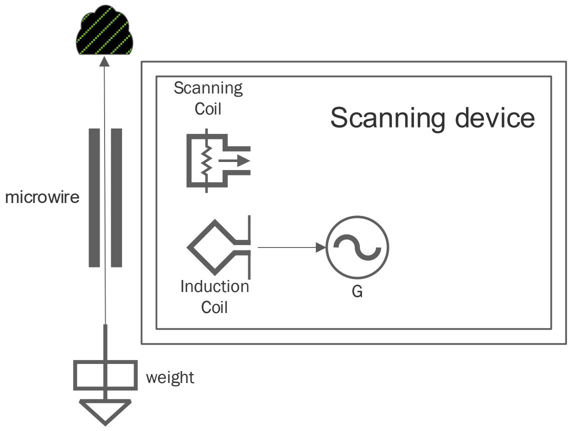

Figure 1. Stand for checking magnetic characteristics response.

Initially a study was performed to find the more appropriate materials with given characteristics which were able to provide a response in the magnetic characteristics when a stretching force was applied. A simple stand (see Figure 1) was designed to perform this preliminary research.

According to the preliminary research for many materials a change in coercive force (*Hc*) was identified, Figure 2. For the measured samples it was identified that microwires reached the strain hardening region, were change in coercive force was relatively low for a wide range of the applied tensile stress. Moreover, many samples were prone to reach the necking region or even broke, which would make the microwires unsuitable to be used as strain sensors.

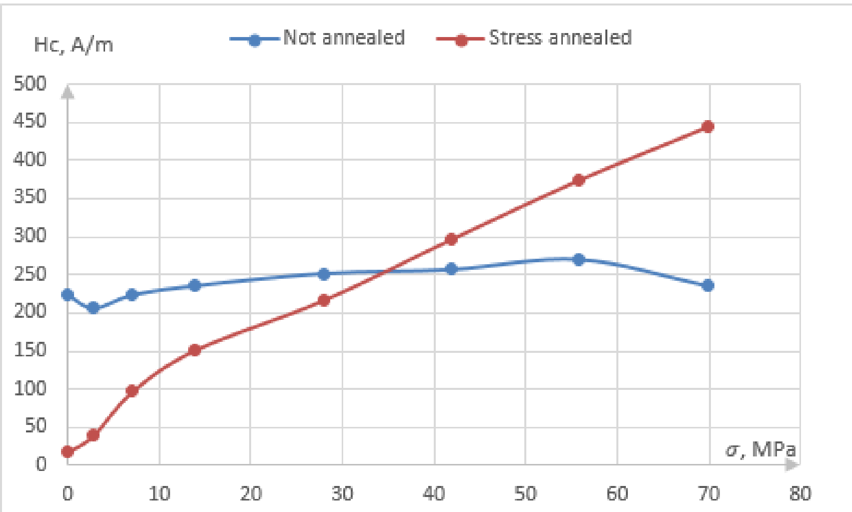

Figure 2. Dependence of the coercive force (Hc) on the applied tensile stress (σ).

Even if some of the studied materials may show low sensibility to stretching, this can be improved by performing annealing or stress-annealing. Stress-annealing of microwires is performed by exposing an amorphous microwire based on ferromagnetic alloy to a higher temperature in stretched state. The exposing temperature is less than crystallization temperature, thus the alloy core keeps the amorphous state, but the closest atomic layer is restructured along the applied force. At this temperature the glass coat almost doesn't change its shape. After stress-annealing, under normal conditions, the tension in the core of microwire is decreased or even has constringent characteristic [10].

Thus, it is very important to perform a research on thermomechanical processing in order to reach higher sensibility for strain sensors. According to preliminary results of research at Microfir Tehnologii Industriale, Ltd, the stress-annealed microwires had a wider range sensibility and depending on material and stress-annealing technology, a wider range of sensibility can be obtained. Thus, a research process for microwires stress-annealing has been developed, to identify the appropriate technological process for various applications. The processing of microwires included research considering various temperature value, stretching forces and speed through processing furnace.

The ratio of the tensile stress for microwires can be calculated according to the expression:

$$\sigma_m = \frac{kP}{kS_m + S_{gl}} \tag{1}$$

where: k is *Em/Egl*: Young's modulus for the used metal (alloy) and glass, P is the applied stretching force, S_{gl} and S_m are the cross sectional areas for glass and used metal. According to the expression (1) a set of weights were used to apply a tensile stress in range of up to 70 MPa.

Considering the impact of stress-annealing and (1), the expression for calculating of coercive force would be:

$$Hc = f(\sigma_m, V_a, T_a) = K_0 + K_1\sigma_m + K_2V_a + K_3T_a, \tag{2}$$

where: V_a and T_a are annealing speed and temperature. K_0, K_1 and K_3 are coefficients which can be identified for a given annealing process and microwire to create a sensor with required characteristics.

The sensible element can be used in applications with contactless measurements for composite materials. By integrating microwire into monitored environment, access to it can be difficult, or depending on the embedding process of sensible element, its response can vary. For this situation a special adjustment procedure should be considered, but this wouldn't be suitable for mass production cases.

The strain measuring characteristics can be significantly improved by using a reference microwire which is strain tolerant, but has an appropriate coercive force to the sensible microwires (Figure 3). Thus, the research process considered also the microwires which have a magnetostriction close to 0. Reference microwire can provide a reference signal which makes the measurement device to be more tolerant on displacement with sensible element. Research process also identified the more suitable reference microwires for sensible microwires with given characteristics. Considering the fact that microwires are based on amorphous materials it is important to perform research on its elastic characteristics. The purpose of this research was to identify the impact of multiple stretching cycles on the microwire characteristics, especially on microwires developed for strain gauge.

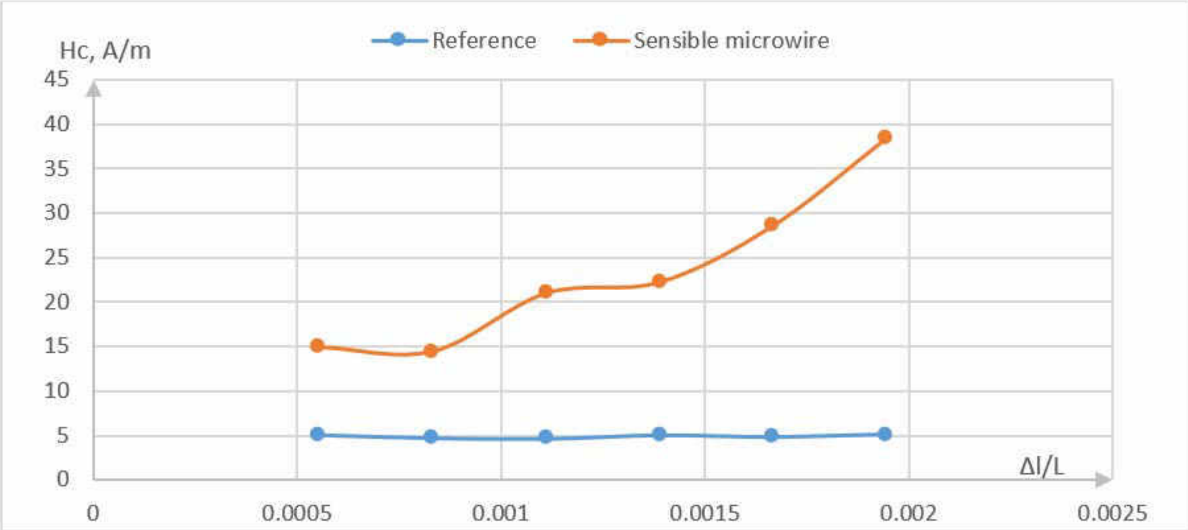

Figure 3. Change in coercive force (Hc) under elastic strain (Δl/L).

For research of microwire magnetic and elastic strain characteristics a system was developed, Figure 4. The system includes the following main parts:

1) plain BH meter designed for embedded sensible microwires;
2) stretching mechanism;
3) support for microwires installation.

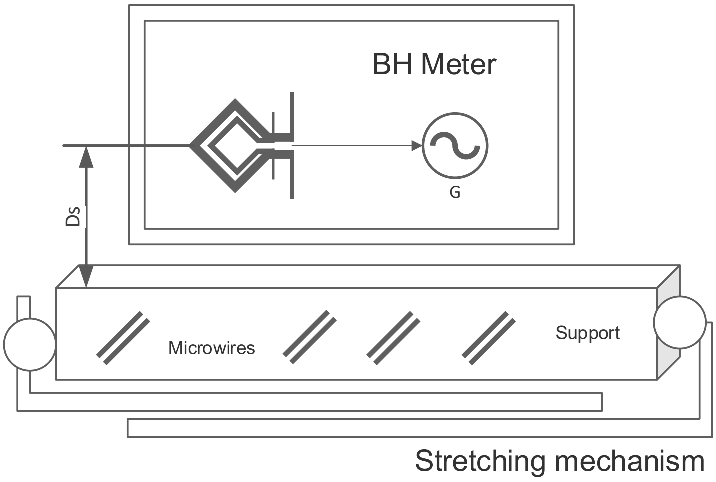

Figure 4. Magnetic and elastic strain charateristics measurements.

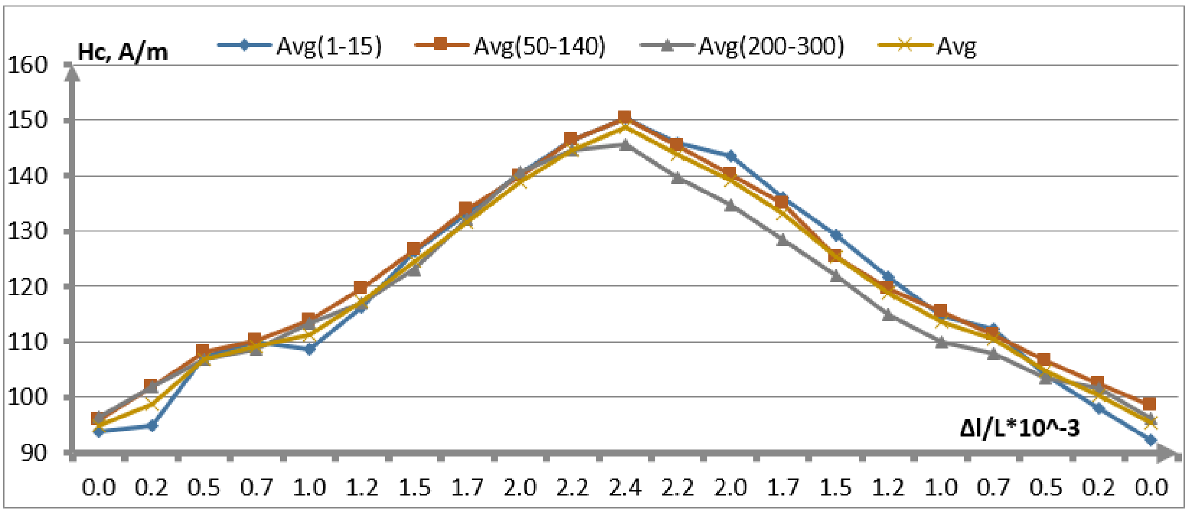

Figure 5. Change in coercive force (Hc) as a function of cyclic elastic strain (Δl/L).

Many microwires could be installed on the measurements support, which made possible to measure characteristics of all the installed microwires in one measurement cycle. According to the performed measurements, the investigated microwires had shown stable sensibility in the range of testing stretch. In large, the magnetic response didn't change over many stretching cycles (Figure 5), thus it can be considered that for elastic stretches the sensibility is stable.

3. Monitoring and control of microwire production

One of the main aspects of the study was radiographic analysis of microwires. Separate research was performed by measuring M-H curves for a few selected samples, which had performance difference in spite they were from the same production lot. It was decided to observe the magnetic, geometrical and chemical properties by employing Scanning Electron Microscopy (SEM). Also, the wires were observed including Energy Dispersive X-Ray Spectroscopy and Electron Back Scatter Diffraction.

Microscopic observations using SEM suggested several facts which can lead to difference in performance for microwire based sensors. For few samples could be inferred that glass coating in respect to its metallic core brings to a better sensor noise. For other samples it was noticed that circularity of the microwires, as well as their uniformity in thickness of the glass coating are very important aspects of stress distribution and homogeneity applied to the metallic core [11].

The outcome of radiographic analysis was that microwire production process based on Taylor-Ulitovskiy method should focus more on parameters tuning and control. The resulting optimization of microwire production should lead to control of microwire geometrical shape and its stability along process. Usage of a standard MR meter during casting is not enough considering that it has accuracy of 5 to 10% with quite narrow limits. Moreover, the MR meter cannot be used for a wide range of microwire diameters. A significant improvement into casting process can bring an intelligent embedded device based on concept of microwire diameter measurements based on optical transparency [12]. This new method can be used for measurement of microwire parameters during casting process [13]. The method can provide such useful information for casting process as core diameter and its glass coat thickness. Thus, it is a way to provide information about process, especially when microwire diameter, circularity and glass coat thickens are critical for its production as strain sensors. Only providing this information in time, during casting can improve the final quality of microwires.

Considering that casting process according to Taylor-Ulitovskiy method represents a harsh environment for measurements of microwire geometrical parameters, a special approach, using edge computing should be designed.

The proposed concept of microwire diameter measurement is based on microwire transparencies for different wavelength. This method is precise enough for large diameters of microwire core and thick glass coat (>*20μm*). For such microwire the casting process is accurate enough to keep its circularity and quality of the glass coat.

While winding, microwire doesn't have a strict position in space and as a result the microwire can touch the edge or fall out of laser beam and light sensor. This leads to mismatch or failed measurements of microwire. A solution for this issue would be reshape of laser beam but for small microwire, the light sensibility can be affected by diffraction processes on microwire or glass coat defects.

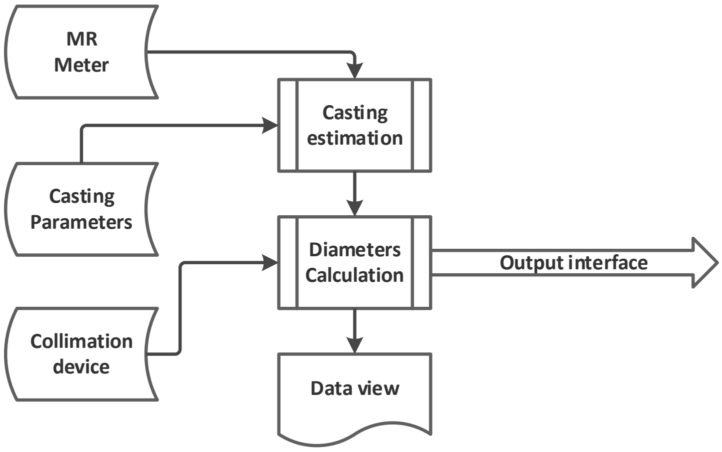

Figure 6. Microwire measurements during casting.

Considering the harsh conditions of casting and special requests for production of microwires for strain gauge sensors, a new device has been developing (Figure 6), which implements some features of the measurement method [12].

The new concept is supposed to be able to measure diameter for a wide range of microwire diameters. The most problematic to measure are the smaller microwires. For these kinds of microwires are required linear scanners with corresponding sensibility into ultraviolet and visible spectrum. The linear scanner may need some factory adjustments or sampling setup during casting. According to the proposed method, microwire diameter can be calculated according to expression:

$$D = (N_{sh} + N_{hsh}\delta_m)\, K_s \qquad (3)$$

The expression above considers the average linear size of microwire diameter *D,* calculated by using linear scanner. The measured linear size is a calculated one, for both linear scanners on which the microwire is projected by a laser beam. The main argument for calculation for the expression (3) is N_{sh} which is the linear size of the shaded pixels. K_s is a noise factor, N_{hsh}- amount of half shaded pixels, δ_m – a gain factor.

Depending on microwire size, the projected shade can be dispersed, especially on the scanner aligned with winding direction. Initial aim for this scanning group was to provide a reference signal for diameter measurement. But smaller size of microwire is, more chances are that microwire can fall out of the beam for this scanning group, which leads to faulty measurements. This issue can be solved by changing the angle of the beam to microwire, but this workaround has a drawback: the quality of reference signal is decreased. To improve the measurement of the signal for the aligned microwire to beam, it was decided to use a linear scanner with improved sensibility in wide range of spectrum. This solution can provide diagnosis of measuring status by checking if the microwire shade is included into scanned area. But, especially for this scanning group, the shading effect is more evident and the sampled data for the half-shaded pixel can lead to improvement of measurement by including it in the calculation expression as N_{hsh} . Because N_{hsh} doesn't represent a strict value, a gain factor should be applied to it - δ_m. The corresponding gain factor is derived from the measured microwire diameter which is performed by MR meter during casting. The sampling on linear scanners are fast enough, but for improvement of measured data in order to obtain a more precise picture, the contrast should be increased. Increasing of contrast should be performed by software, by a digital image filter, which in the end leads to a late response. Also depending on microwire position as a result of winding, naturally a noise is applied to the filtered signal. This noise (K_s) can be included as gain factor into calculation formula (3):

$$K_s = f(V, A) = k_v V + A, \tag{4}$$

where: V is the linear speed of winding, and A represents a set of ambient factors which reflects ambient light, environment temperature etc.

The microwire diameter measurement device (Figure 6) embeds many hardware components and stand-alone systems. The key component is the collimation device which has at least two collimation groups which use lasers in the visible spectrum (~700 nm) and two collimation groups which use ultraviolet light emitters [200 nm:400 nm].

Assembling of collimation group is a complicated process which require alignment of many components (lens, sensor, laser) and its positioning into microwire winding area. The result of alignment is not perfect and requires post adjustment which is possible to be performed digitally. As a result, a collimation group should represent stand-alone embedded device with capability of adjustments depending on assembly result and cast machine environment or setup. Thus, the collimation group should be equipped with input interfaces to assure an appropriate adjustment during casting, also it should provide the measurement of N_{sh} and N_{hsh}.

Also, an important aspect for calculation of N_{hsh} and K_s is the connectivity to casting device and the included MR meter. The required measurements and calculation are performed by casting machine, which defines it as an edge computing device, as well as diameter calculation device.

4. Non-contact application approach: a case study

The main application of SGM are the devices which basically requires contactless measurements. For these applications it is important to embed the sensible element into the body of device which is affected by elastic deformations. Considering that SGM provide strain response into its magnetic characteristics, SGM can be embedded in composite or other non-magnetic materials.

Along with structural health monitoring systems, an application example is the composite gasbags which integrity can be affected by aging or bad operation. The SGM can provide useful information to prevent or identify early potential risks of cracking on monitored devices. The proposed approach can be used in various non-contact applications where it is necessary to measure the deformations of bodies subjected to stretching, such as, for example, the detection of critical deformations in high-pressure composite cylinders. In this case, the sensor itself can be fixed on the inner lining of a high-pressure composite balloon, and the embedded device (an edge computing device) can signal a possible deformation state by scanning the surface of the composite cylinder.

Considering that developed SGM are intended to be used in environments with a wide range of temperatures (negative temperatures up to 50 °C, depending on device specific requirements), it is required to developed a prototype of edge computing device (ECD). The developed ECD, should be able to manage measurement of SGM along with magnetic response from a reference microwire which characteristics is not affected by temperature.

When the detection device approaches a body on which the sensor is fixed, the magnetic field generated by a sinusoidal alternating current (*Mag* signal in Figure 7) acts on the sensitive wire (*Smr* signal in Figure 7) and on the reference wire(*Ref* signal in Figure 7).

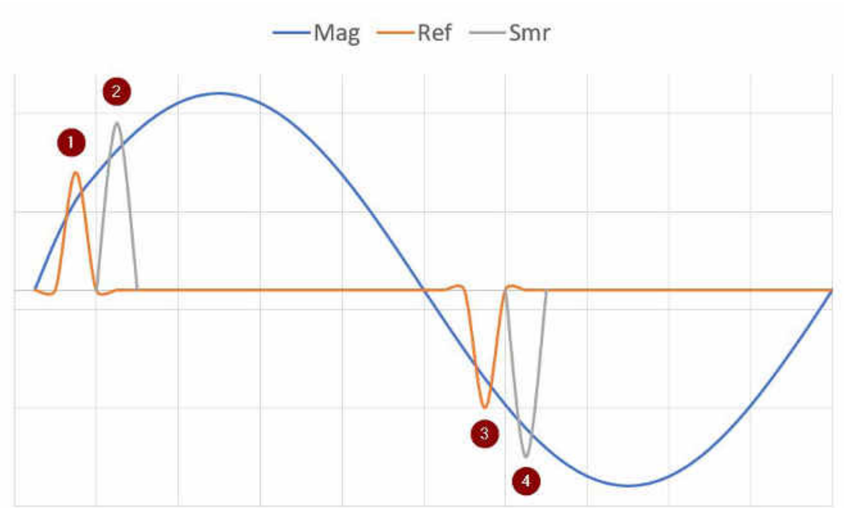

Figure 7. Magnetic response of reference and sensitive microwires.

Due to the bistable behavior upon remagnetization, the magnetic response of the sensor is characterized by a giant Barkhausen jump, which allows the induction of short electromagnetic pulses 1 - 4. Pulses 1 and 3 (Figure 7) induced upon remagnetization of the reference wire, respectively, pulses 2 and 4 (Figure 7) induced upon remagnetization sensitive wire are of sufficient amplitude to be detected by the detection device. The magnetic response of the sensor to the applied alternating magnetic field depends on the tensile strain. In other words, the change in the magnetic characteristics of the hysteresis loop is correlated with the deformation to which the magnetic material is subjected. In the case of the sensitive thread, the area of the hysteresis loop, respectively the coercive force increases with the tensile strain. At the same time, the area of the hysteresis loop, respectively the coercive force of the reference wire, does not depend on the stretching deformation. The magnetic response of the sensor can be determined by detecting the electromagnetic pulses induced upon remagnetization and calculating the numerical value of the ratio of the hysteresis loop area of the sensing wire to the hysteresis loop area of the reference wire. The resulting value must be recalculated according to the stretch sensibility coefficient of the sensitive wire with an algorithm built into the ECD. The result obtained from the calculations will represent the size of the deformation, which, in general, does not depend on the distance from the detection device (Figure 4 - sensing distance *Ds*). Thus, by applying the method of comparing the magnetic characteristics of the hysteresis loops of the sensitive wire and the reference wire, the magnitude of the deformation of a solid body can be determined (5):

$$\frac{S_{smw}^{loop}}{S_{smw}^{loop}} => \varepsilon, \tag{5}$$

where: S_{smw}^{loop} is the hysteresis loop of the sensible microwire, S_{rmw}^{loop} represents the hysteresis loop of the reference microwire and ε is the elastic strain. Considering that many parameters of the measurement device are constant or doesn't vary, the elastic strain can be calculated by using a lookup table (Figure 8), which can be adjusted during device calibration. It should be noted that such a non-contact strain sensor/device can be easily mounted on the surface of the solid body, in the example given on the inner lining of the balloon, due to the fact that the microwire segments are located close to each other and can be easily integrated into the technology existing manufacturing of high-pressure composite cylinders.

5. Predictive maintenance based on contactless sensors

The embedded SGM can provide useful information about operating conditions but the aim is to include them into complex systems designed to provide more data about the system itself. All the acquired data, along with strain measurements, can be processed by edge computing device in order to identify the system behavior patterns, which leads to certain defects or identify the required maintenance to improve costs or operations.

A new system for predictive maintenance is being designed, Figure 8. The system is supposed to implement monitoring and control of wind turbine (WT) blades. One of the key elements to provide the online state of the turbine are the SGMs that are embedded into the blades.

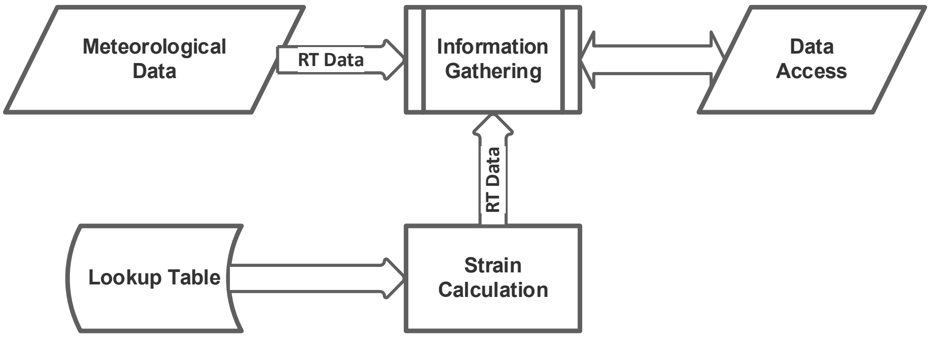

Figure 8. System for predictive maintenance.

In the above system the strain calculation should be performed in real time. Due to its complexity, these systems are built by using plug and play devices. This general criterion should be followed also by strain calculation module (SCM). Thus, the strain calculation module should represent an embedded device with corresponding to the industry input/output interfaces which would be able to provide real time data accordingly.

Embedding of microwires into blades can be a custom process in the plants, the same as installing of excitation and scanning coils for microwire. Thus, the final characteristics of the strain reading device can vary due to production process. The SGMs had a well-defined characteristic and the elastic deformation can be estimated by using a lookup table, but considering that adjustments are required, the SCM should implement an interface for calibrations and update purposes.

To implement a reliable solution for predictive maintenance all the environment factors should be considered. For WT the main inputs for prediction of the required service would be all the meteorological data. Of course, the wind power and its gusts are the main environment factors which can significantly affect WT state but there are also many other factors which in long terms has a huge impact: ultraviolet light, temperature, icing, humidity. To measure the status for all of these factors the corresponding embedded device should be implemented.

Meteorological data and SCM provide all the required real time data to an information gathering system. Depending on the scale of WT farm and purpose of maintenance, the provided data can be used combined with a cloud system which implements a predictive maintenance model, or considering the performance of modern micontrollers and its machine learning capabilities [14] or AI oriented solutions, the model can be implemented as standalone solution.

Considering the latest researches about WT blades reliability [15], the importance of the designed systems is imperative. According to research, various models were studied in order to identify the fatigue reliability or fatigue failure probability. The state-of-the-art reliability analysis was focused on two most important categories:

1) Fatigue reliability analysis calculating the probability of blade fatigue life that is greater than a target lifespan under fatigue loadings, which is difficult to estimate under complex loading.
2) Extreme reliability analysis evaluating the probability of blade performances (e.g., deflection and stress/strain) that satisfy the designed threshold under extreme loading (e.g., wind gusts). For this category the analysis is problematic due to various inherent randomness and external uncertainties that affect the fatigue life of blades.

The challenging factor for study is mainly due to the complexity of the fatigue degradation principles of blade materials, limited information available on blade fatigue experiments and the very sophisticated fatigue analysis procedure. Analysis was focused on identifying calculation methods relying on some construction aspects, abstraction of its structure (beam-like) or even identifying some key environment condition (wind gusts and its instantaneous stress) which would have a big impact on structures reliability.

Even if some identified prediction models seem to be veridical, one of the difficulties that reliability analysis of wind turbine blades faces is the lack of validation cases for the reliability analysis results due to the rare records of blade failures under all range of loadings. The background of this validation fail is the lack of blade strain measurements and elastic deformations. Thus, the developed predictive maintenance system using SGMs (Figure 8) can become also a research system for both evaluation of failure analysis and various design of blades.

5. Conclusions

Nowadays the area of sensors applications is widened along with complexity of tasks to be resolved based not only on sensors itself but also as a component of highly integrated embedded systems. SGMs are non-contact sensors and its applications are very specific. Thus, a special workflow was designed to develop the microwires depending on application. The workflow includes identifying of needed alloys, validation of casting process and methods of microwire stress annealing to provide an appropriate strain sensor. The developed SGMs provide remarkable characteristics and can be embedded into composite materials, and along with latest technologies designed for edge computing device and ML, they are suitable for predictive maintenance and failure analysis of different engineering objects and structures.

Conflicts of Interest: The authors declare no conflict of interest.

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