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DESIGN AND ASSEMBLY OF AN APPARATUS SYSTEM BASED ON THE VILLARI EFFECT FOR DETECTING STRESS CONCENTRATION ZONE ON FERROMAGNETIC MATERIALS

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Summary

This paper presents the study results on the fabrication of a structural integrity assessment apparatus by determining stress concentration zones in pressure pipeline and equipment. The apparatus uses a triaxial magnetic field sensor to measure magnetic field components in three axes Ox, Oy, and Oz, in the working range of the magnetic field from -300 µT to 300 µT. The investigation of the self-magnetic leakage field by this apparatus in the API 5L steel specimens under tensile stress shows a high variation of the magnetic field at a steel elongation lower than 1 mm (corresponding to the elastic deformation state of the material). In the case of an artificial defect, the apparatus can detect a change in the magnetic field caused by stress concentration.

Key words: Magnetic field apparatus, stress concentration zone, integrity assessment, defect detection, self-magnetic flux leakage.

1. Introduction

Non-destructive testing (NDT) is a technology widely used in the inspection of the integrity of equipment and pipes in operation. It is used by the industry to evaluate the properties of a material, component, structure, or system for characteristic differences or welding defects and discontinuities without causing damage to the original part. Early detection of defects in metal structure is very important, allowing timely replacement and repair. Therefore, factories can operate safely, save repair costs, and avoid possible disasters [1]. Non-destructive testing consists of different methods, usually divided into two main groups according to their ability to detect defects:

NDT methods can detect the defects and discontinuity in and/or on the metal surface of inspected component and structure: Radiographic testing (RT), Ultrasonic testing (UT).

Other NDT techniques can detect only the defects on the metal surface or near the surface: Liquid penetrant testing (PT), Magnetic particle testing (MT), Eddy current testing (ET).

The advantage of NDT methods is that they may inspect the pipe and equipment online during operation. However, these methods need direct contact with the metal surface, whereas it is difficult to access some locations such as underground or/and submerge pipelines; pipes and equipment under insulation or under support, etc. To satisfy practical requirements, the study, development and testing of a non-contact NDT apparatus are necessary. Among the non-contact testing methods, the magneto-mechanical methods are used with a wide range of applications.

Joule magnetostriction is a property of magnetic materials that causes them to change their shape or dimensions during the process of magnetisation [2]. The structure of ferrous material is divided into small magnetic domains, which are randomly orientated when the material is not exposed to a magnetic field. When a magnetic field is applied, the magnetic domains shift and rotate causing a change in the material's dimensions as shown in Figure 1.

The inverse magnetostrictive effect, magnetoelastic effect or Villari effect characterises the change of the magnetic susceptibility of a material when subjected to mechanical stress [3]. Pressure pipelines and equipment are typically subjected to internal or external corrosion, which can weaken their structural integrity. The pressure

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and bending stresses applied to the corroded sections will result in stress concentration. Measurement of the stress concentration zone (SCZ), as well as detection of the micro-defect growth, has been of high importance for predicting the location of mechanical failures and evaluating the remaining useful lifetime (RUL) of pipelines [4].

The metal magnetic memory (MMM) technique, which was originally developed in Russia in 1997 [5], is based on the Villari effect [6 - 7], in which the application of stress on a ferromagnetic material causes the rearrangement of magnetic domains. When this occurs in the presence of an external magnetic field such as the Earth's magnetic field, a relatively large magnetisation change will be caused (Figure 2). By measuring the residual magnetic leakage field (RMLF) distribution on the material surface, the MMM method has been implemented as a periodic screening inspection tool, evaluating the degree of stress concentration [8 - 9]. This technique is a promising tool for inspecting early damage due to stress concentration in ferromagnetic components by testing and analysing the magnetic leakage field (MLF) above the surfaces of the components in the geomagnetic field [10 - 13]. The technique seems rather similar to the magnetic flux leakage testing technique since both need to measure the magnetic field surrounding the ferromagnetic components, but their discrepancy is remarkable. The magnetic flux leakage testing must impose a high intensity magnetic field and is mostly used to inspect geometrical defects such as holes; whereas the MMM technique only utilises the natural weak geomagnetic field (the Earth's magnetic field) and is more sensitive to stress. Usually, there are possibly both geometrical defects and local stress concentration zones in ferromagnetic components. In fact, the MLF signals incorporate the effects of geometrical defects and stress concentration zones, in which the former perturbs the MLF path and the latter induces the local magnetic anisotropy [10]. A significant advantage of this MMM method is that it can detect the SCZ, and thus high areas of stress, giving it the ability to predict regions where anomalies are developing before they become failures. The ability to detect SCZ means that using this method, it is possible to analyse all areas that are exposed to high stress, including anomalies, corrosion and bending stresses, making the method more comprehensive than the existing technologies. However, the magnetic field variation caused by SCZ is small, of the order of 10 µT, which is a variation in the background (Earth) field of 40 - 60 µT, and as such the measurement of this appears daunting [4]. With the advent of small portable magnetometers, the measurement and interpretation of these signals have become a practical proposition.

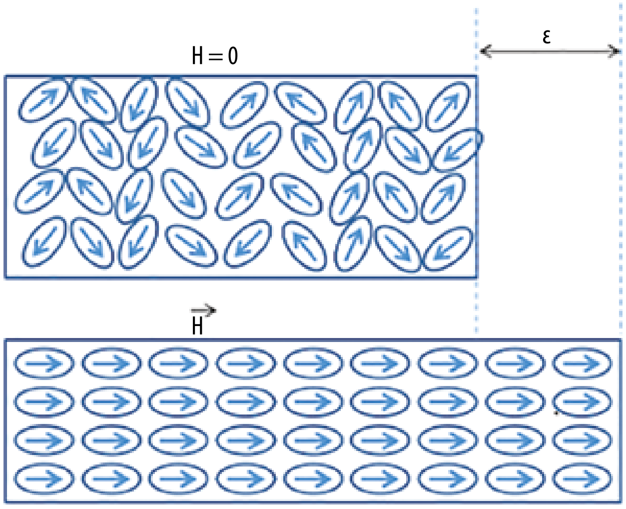
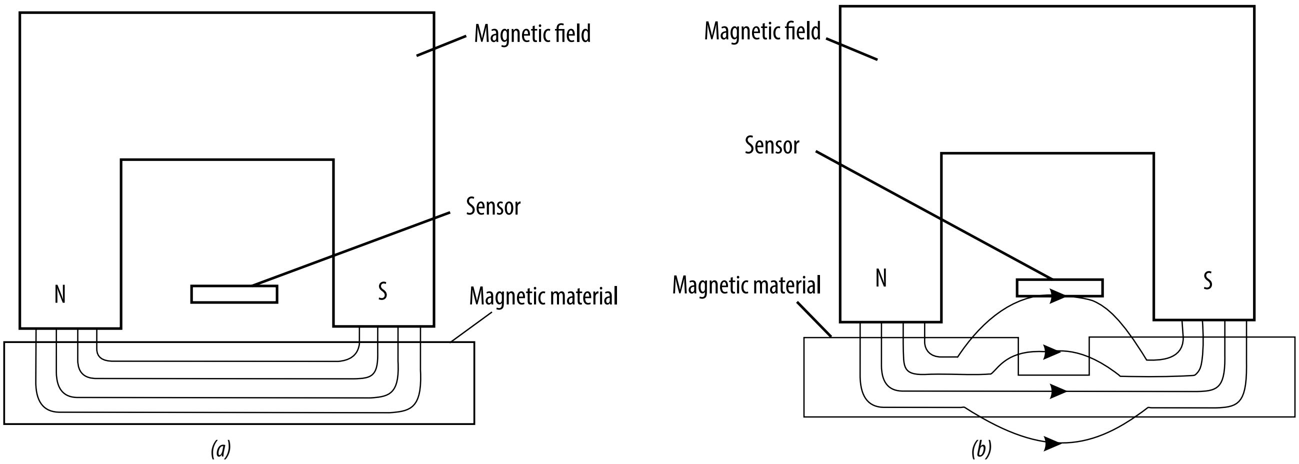


Figure 1. *The magnetostriction effect - an applied magnetic field causes the alignment of magnetic dipoles and thus the change in length of a given sample.*



(a) *(b)*

Figure 2. *Magnetic leakage field from the magnetic material without (a) and with (b) a defect.*

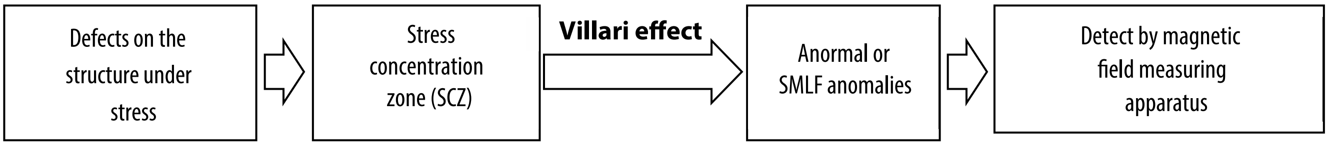


Figure 3. *Diagram of the principle of applying the Villari effect in the defect detection.*

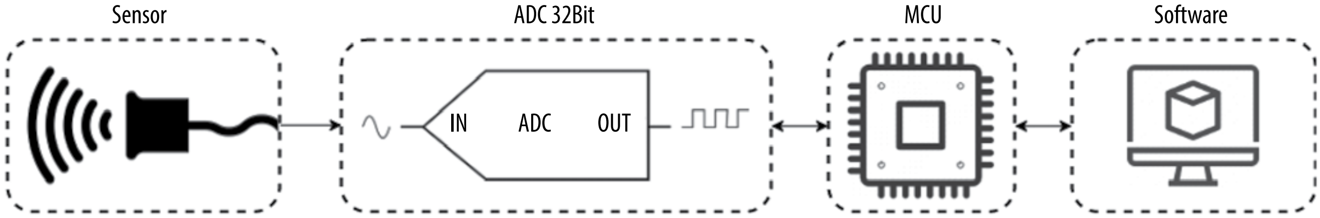


Figure 4. *Block diagram of apparatus.*

In Vietnam, studies and development of the magnetoelastic Villari effect are still very limited [15]. It is, therefore, necessary to design and fabricate a device or apparatus which can detect the "natural" SMLF that escapes from anomalies and SCZ without the requirement of an applied external magnetic field. This paper introduces the magnetic field measuring apparatus fabricated by the Vietnam Petroleum Institute (VPI) and some initial results of detecting the stress concentration on ferromagnetic speciments under tensile stress.

2. Design and assembly of magnetic field measuring apparatus

2.1. Apparatus design

The main board of the apparatus is a control intergrated unit which includes sensor block, amplifier into noise filter, analog-to-digital converter (ADC) and communication block.

The sensor is a three-dimensional (3D) type of Honeywell with high sensitivity, a magnetic field sensor according to the Giant magnetic field - GMR. This is a hybrid sensor consisting of one dual-axis sensor and one single-axis sensor with a measuring range of ± 2 Gs.

The amplifier into the noise filter block is a component that filters noise from the environment. In the research to fabricate this device, three-level amplification was used.

The analog-to-digital converter (ADC) is a system that converts the analog physical quantity continuously received from the sensor to a digital value to represent the magnitude of that quantity. Magnetic sensors can receive magnetic signals through output voltage signals. ADS1262 IC ADC with very high resolution, programmable amplifier and good noise resistance was selected.

A communication block controls a bi-direction connection between device and computer for monitoring, controlling and data collecting.

2.2. Investigation of magnetic sensor characteristics

The sensor is a linear magnetic field transducer whose output is a voltage proportional to a magnetic field applied perpendicularly to the package top surface. To verify the characteristic of the sensor, the relationship between the output voltage of the sensor and the applied external magnetic field is investigated.

The applied magnetic field is uniform, generated by Helmholtz coils, in which the intensity of the magnetic field is controlled by a constant current source; the sensor's output signal is picked up via a high-precision voltmeter, which connects to the computer. The relationship between the sensor output signal and the external magnetic field is described in Figure 5.

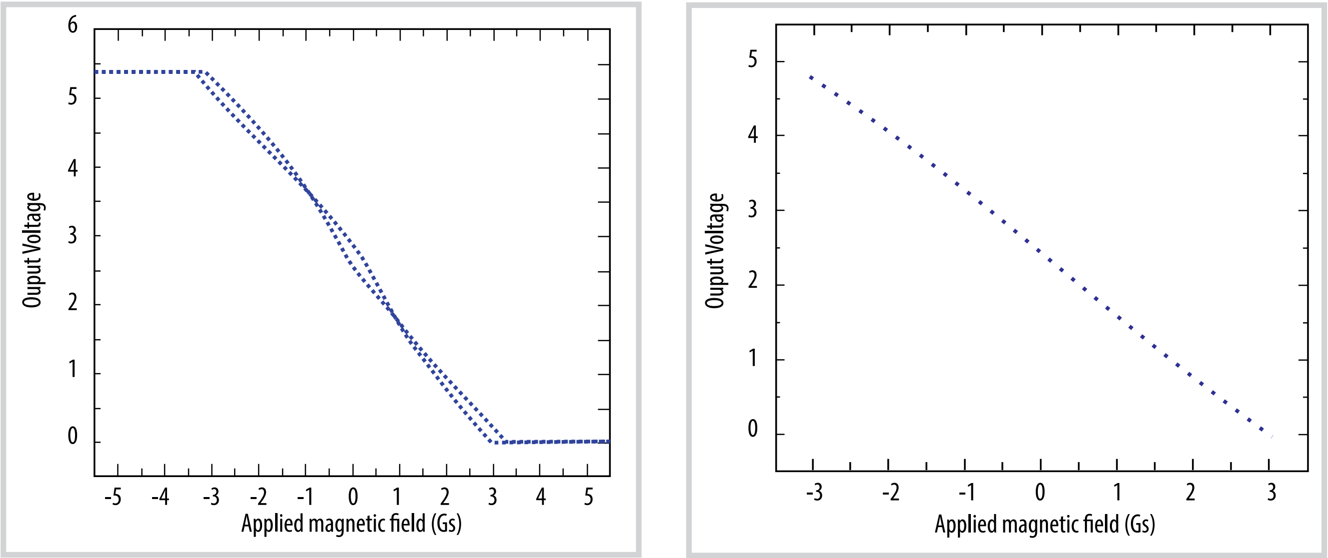
The obtained results show that the variation of the output voltage of the magnetic sensor following the applied external magnetic field is linear in a magnetic range from -3Gs to 3Gs (corresponding to -300 μT - 300 μT). Beyond this working range, the sensor is in a saturated state. This selected sensor is suitable for detecting the self-magnetic leakage field.

The testing apparatus was assembled and configured to determine the stress concentration zone of the defected steel specimens.

3. Experimental condition

3.1. Specimen preparation

The testing specimens are made of API 5L steel, which is the material widely used to manufacture the



(a) (b)

Figure 5. *Relationship between the output voltage signal of the sensor and the applied external magnetic field in two axes x (a) and y (b).*

(a) (b)

Figure 6. *Testing specimens and measuring points (a) and the artificial defect (b).*

transportation pipelines of oil and gas. The shape of the flat specimen is shown in Figure 6. Its surface roughness Ra is 1.6 mm; two parallel lines marked with 6 mm of space vertically are drawn on the surface. There are 11 points with 10 mm intervals on every horizontal line chosen for magnetic field measurement. The length of each measured line is 100 mm.

To create a stress concentration zone, an artificial defect is made in the middle of the specimen and then tensile stress is applied to the specimen. To avoid residual stress in the specimen affecting the results of the test, the artificial defects are created by electrochemical corrosion. The shape, size and depth of the defects are controlled by the active surface of the metal specimen (the surface contacts directly with electrolyte) and the electric charge flowing through the specimen.

3.2. Tensile stress

To evaluate the ability of the apparatus to detect stress concentrations by the magnetoelastic effect, the specimens were stretched by a mechanical DLR testing machine. During the tensile test, each specimen is positioned vertically between the upper and lower grip holders of the testing machine. Tensile stress is loaded on the specimen through the elongation of the specimen. The magnetic field values of all points on each measured line were collected at a predetermined elongation. After the measurement, the specimen was loaded again to a higher elongation, and the above procedure was repeated until the specimen broke.

3.3. Magnetoelastic measurement

The magnetic field values were measured by our self-fabricated apparatus. The magnetic sensor of the apparatus is fixed at a distance of 2 cm from the specimen surface and could move along the direction of measured lines vertically, and the measurement data are collected at 11 points (from point -5 to point 5 beside the defect (point 0)).

4. Results

The change of the self-magnetic leakage field along the length of the metal specimen with artificial defects under tensile stress has been investigated by the self-fabricated device. The sensor was moved parallel to the specimen surface at a distance of 2 cm away. The magnetic field signals were collected in three axes of Ox, Oy and Oz of the sensor (Ox is the vertical direction, Oy is a horizontal direction and Oz is the perpendicular direction to the specimen surface). The values of the magnetic field at points -5, -4, -3, -2, -1 and 1, 2, 3, 4, 5 were compared to artificial defects (point 0) at different levels of specimen elongation.

Figure 7 shows the variation of the magnetic field with the elongation of the specimen, corresponding to tensile strength. The obtained results showed that the magnetic field varied very strongly at an elongation range lower than 1 mm. When the specimen was stretched with an elongation higher than 1 mm, corresponding to a relative elongation above 0.5%, the magnetic field tended to be less variable. Therefore, we can confirm that the metal specimen is at an elastic deformation state when relative elongation is lower than 0.5%.

The variation of the magnetic field obtained along with the metal sample at different measured points was shown in Figure 8. Since the direction of the tensile force (along the specimen length) is in the same direction of the Ox axis, the self-magnetic leakage field in the Ox direction is the greatest variation. When the relative elongation of the specimen is lower than 0.5%, corresponding to the elastic deformation state of the metal specimen, it is visible to detect the defect position through the change of the self-magnetic leakage field escaping from the defect. However, when the elongation is more than 0.5%, the metal may transform to a plastic deformation state, the

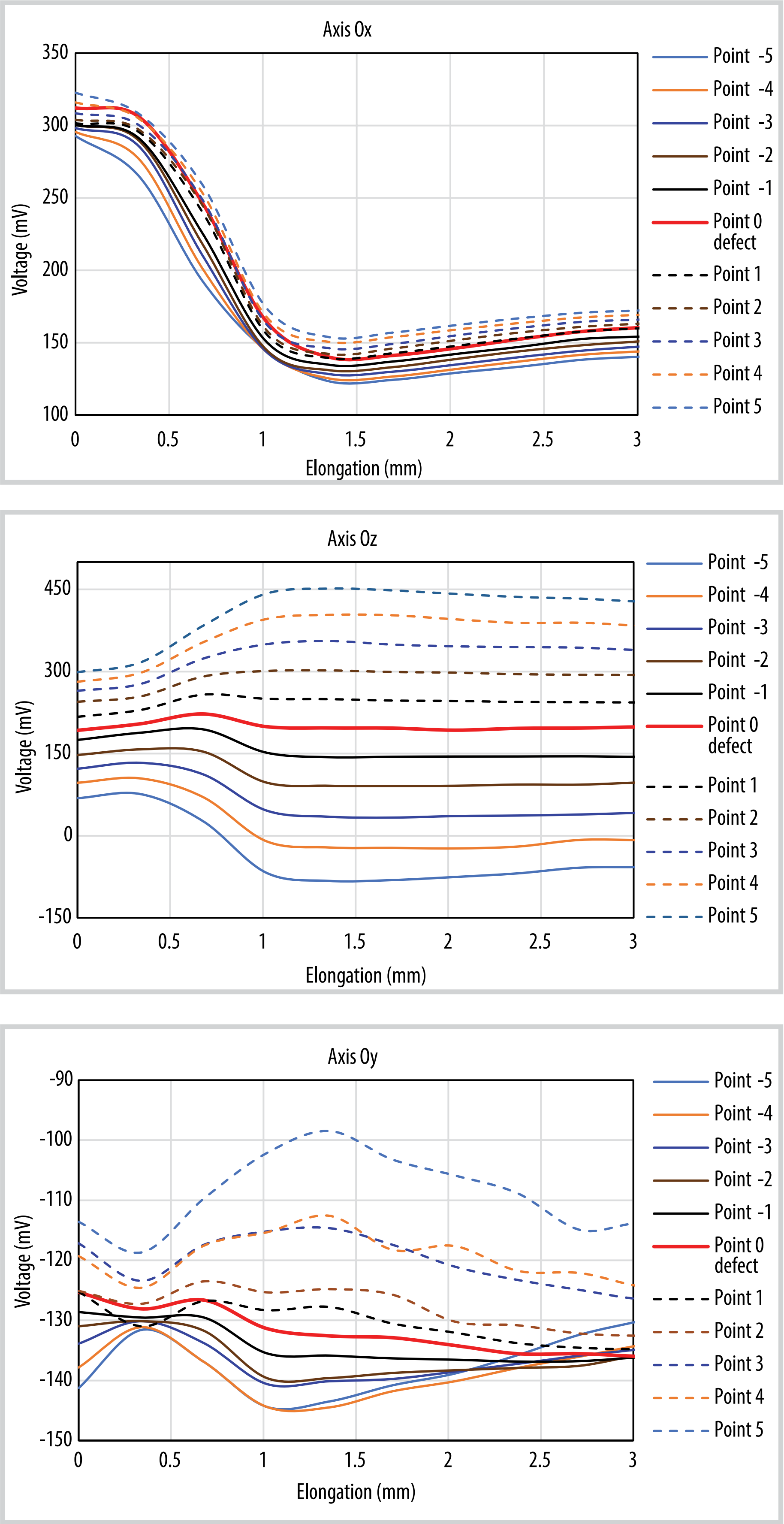


Figure 7. *Variation of magnetic field with elongation of the specimen.*

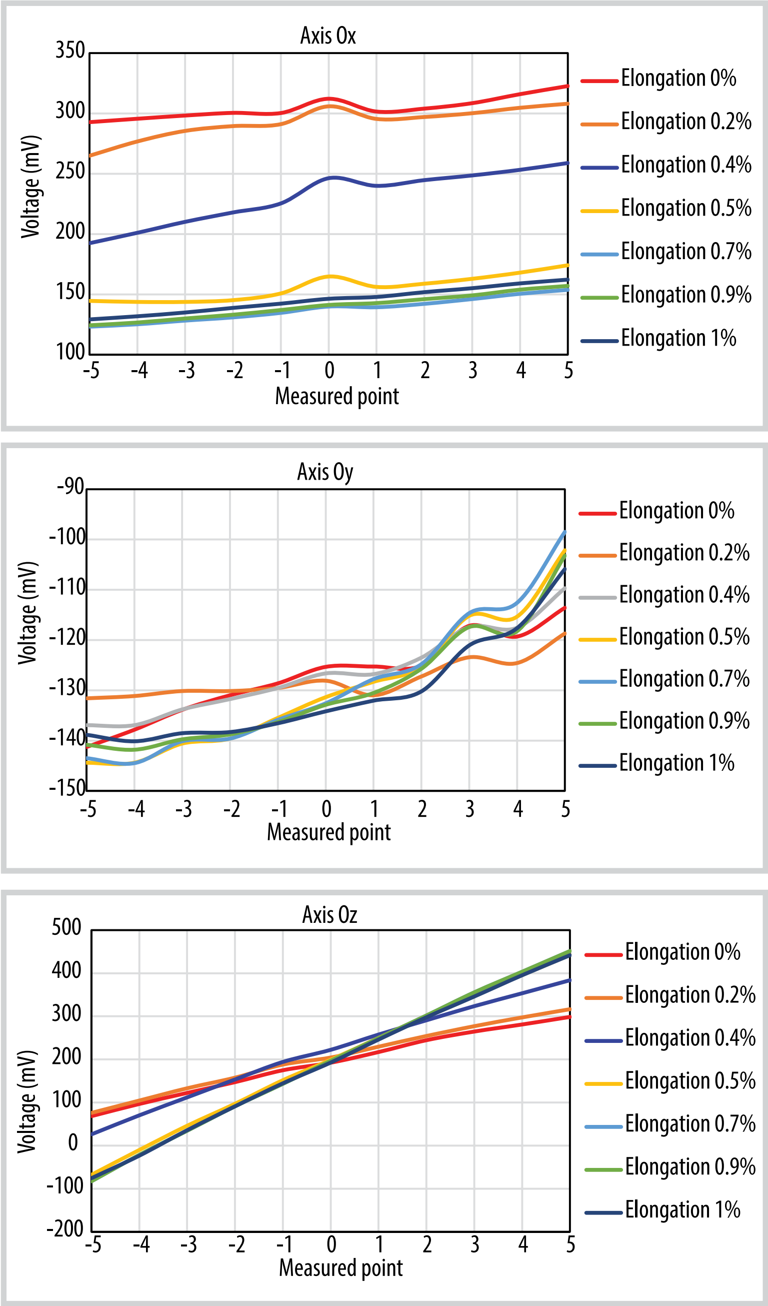


Figure 8. *Variation of magnetic field along the specimen length under tensile stress.*

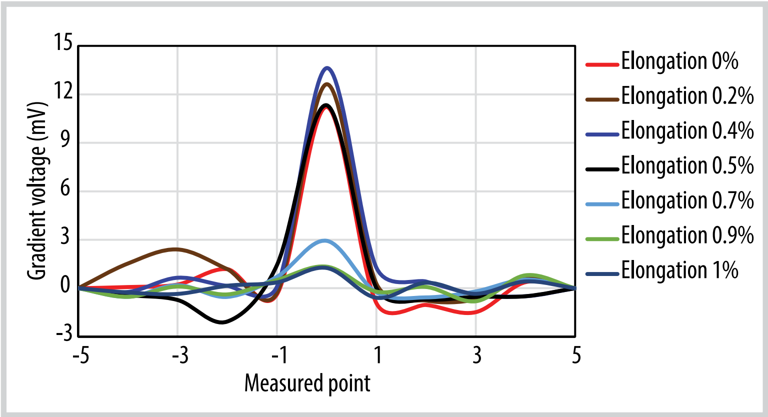


Figure 9. *Variation of magnetisation gradient along the specimen length under tensile stress.*

magnetic moment reaches a saturated state so the magnetic field is less variable and the difference of the magnetic field is not visibly observed at the defect position.

The pressure pipelines and equipment always operate in the elastic deformation state of the material. Therefore, the fabricated apparatus can determine the abnormal magnetic leakage field at or near the defects of the ferromagnetic components, allowing the practical application.

In addition to the Earth's magnetic field, the measured self-magnetic leakage field escaping from stress concentration of the ferromagnetic specimen, also includes the magnetic fields of other sources in the environment such as electric resources, other magnetic materials, if any). So, to eliminate undesired magnetic fields and observe only the self-magnetic leakage field from the defect, the magnetisation gradient was determined along the length of the testing specimen as described in Figure 9. The results also show that in the elastic deformation zone, the highest gradient magnetic field can be observed at the defect location (point 0), corresponding to the stress concentration zone. This confirms the ability of the apparatus to detect the defect through abnormal magnetisation positions.

5. Conclusion

Based on the magnetoelastic Villari effect, a magnetisation measurement apparatus has been successfully designed, assembled and tested, with a working range from -300 μT to 300 μT. The investigation of the self-magnetic leakage field has been carried out by this apparatus in the API 5L steel with an artificial defect under tensile stress.

The results show that a high variation of the magnetic field can be observed at an elongation lower than 1 mm (corresponding to the elastic deformation state of the material). In case of a defect, the apparatus can detect a change in the magnetic field due to the stress concentration. Therefore, this apparatus can be developed and used to inspect the integrity of equipment and pipes without direct contact.

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