46th Annual Review of Progress
in Quantitative Nondestructive Evaluation
QNDE2019
July 14-19, 2019, Portland, OR, USA

QNDE2019-6973

NON-CONTACT MAGNETIC CHARACTERIZATION OF STEEL STRUCTURES

Aroba Saleem, P. Ross Underhill and Thomas W. Krause[1]
Department of Physics and Space Science, Royal Military College of Canada
Kingston, Ontario, Canada

ABSTRACT

Pipelines are the primary means of land transportation of oil and gas globally and pipeline integrity; is therefore, of high importance. Failures in pipelines may occur due to internal and external stresses that produce stress concentration zones, which may cause failure by stress corrosion cracking. Early detection of stress concentration zones could facilitate identification of potential failure sites. Conventional non-destructive testing (NDT) methods, such as magnetic flux leakage, have been used to detect defects in pipelines; however, these methods cannot be effectively used to detect zones of stress concentration. In addition, these methods require direct contact, with access to the buried pipe. Metal magnetic memory (MMM) is an emerging technology, which has potential to characterize stress state of underground pipelines from above ground. The present paper describes magnetic measurements performed on steel components, such as bars and tubes, which have undergone changing stress conditions. It was observed that plastic deformation resulted in modification of measured residual magnetization in steels. In addition, an exponential decrease of signal with distance of the sensor from the sample was observed. Results are attributed to changes in the local magnetic domain structure in the presence of stress, but in the absence of an applied field.

Keywords: Metal magnetic memory (MMM), pipeline inspection, Non-destructive testing (NDT).

NOMENCLATURE

E_σ	Magnetoelastic energy
λ_s	Saturation magnetostrictive constant
σ	Applied stress
θ	Angle between the saturation magnetization of the domain and applied stress
B	Magnetic flux density

1. INTRODUCTION

Metal magnetic memory (MMM) method is a passive magnetic non-destructive testing (NDT) method that doesn't require application of an external field. It is based on the principle of the magnetomechanical effect (Villari effect or piezomagnetic effect) for which magnetization of ferromagnetic material occurs in areas of large strains due to exposure to working loads [1]. It is defined as the change in internal magnetic field in response to the stress applied to the material [1, 2]. Magnetic domains within ferromagnetic materials are oriented in a manner that minimizes their total energy by optimizing flux closure of domain configurations [3].

When stress is applied to a steel material, the magnetic domain configuration energy is modified and a reconfiguration of the domain structure results in a magnetization of the material. Therefor, the effect of stress is similar to the effect of an applied magnetic field. The magnetoelastic energy of a material under stress can be written as [2, 3]:

$$E_\sigma = \frac{3}{2}\lambda_s \sigma cos^2\theta. \quad (1)$$

In order to minimize this energy, domains most closely aligned with the stress direction will shrink or grow depending on the sign of $\lambda_s\sigma$. This implies that stress can cause a change in magnetization. This effect can be amplified by a stress concentration due to a defect. This change in magnetoelastic energy under stress modifies the balanced energy state of the material. To compensate, the magnetoelastic energy is converted to magnetostatic energy by the formation of dipole moments. The change in energy generates an effective force, which results in the movement of domain walls over pinning barriers. This is explained in detail in [4], where a relation is developed between stress and width of excess domain created due to stress.

Pipelines are self-magnetizing due to magnetoelastic effect in stress concentration regions due to working loads. For example, an underground steel pipe that carries a high pressure fluid or gas will be subjected to stress from its internal pressure,

[1] Contact author: Thomas.Krause@rmc.ca

together with any stress due to other sources, such as ground movement. This will generate residual magnetization in the pipe. The manufacturing process of the pipe may also cause additional magnetization. In addition, stress concentration zones and anomalies cause a local change in magnetic permeability, which allows magnetic flux leakage at that point [2, 5, 6]. This implies that magnetic variations are maximum near anomalies and stress concentration zones. Thus, it should be possible to detect these regions by a measurement that is above the ground and non-invasive. However, the range over which this phenomenon may extend and the influence of other neighboring magnetization sources, including the presence of Earth's magnetic field, needs to be accounted for. In the present study, effect of bending on the residual magnetization of a steel bar and tube has been investigated. In addition, the liftoff distance up to which these stresses can be detected by the sensor has been identified.

2. MATERIALS AND METHODS

Measurements were performed on structural steel samples with different shapes, dimensions and degree of deformation. The dimensions of the samples are listed in TABLE 1.

TABLE 1: SHAPE AND DIMENSIONS OF THE STEEL SAMPLES USED FOR MEASUREMENTS.

Sample	Shape	Length(mm)	Width/Outer diameter (mm)	Thickness (mm)
Sample 1	Bar	275	19	3
Sample 2	Bar	560	19	3
Sample 3	Tube	1170	32	1.8

Measurements were performed in the laboratory on stressed and unstressed steel samples using a Honeywell 3-Axis (HMC 5883L) anisotropic magnetoresistive (AMR) sensor with 4.5 milliGauss (mG) resolution and ±8 Gauss maximum field range. This sensor was used to detect 3 components of magnetic flux signals over a sample's surface, simultaneously. Scans were performed from one edge of the sample to another with a step size of 10 mm and liftoff distance changed from zero (contact) to 160 mm.

3. RESULTS AND DISCUSSION

The normal magnetic field component obtained from magnetic scans (at different liftoffs) on Sample 1 after bending is shown in **FIGURE 1**. The normal field component exhibited two peaks, near each end of the sample, and the flux density changes from positive to negative from one end to the other. The transition from positive to negative field was observed near the 75 mm position along the x-axis. It was observed that the signal decreases exponentially with increase in liftoff as shown in **FIGURE 2**. Best fit for exponential decay of the normal field with liftoff is

$$y = 13 + 478 * \exp\left(-\frac{x}{28}\right). \tag{2}$$

As shown in **FIGURE 2** even beyond 90 mm liftoff, there is still a significant field from the sample. From equation (2), the exponential decrease in field with liftoff for the bent sample had a decay constant of 28 mm. Assuming that the liftoff decay constant scales as the pipe diameter, this implies that MMM method could be used to detect stress concentration zones in pipe even without surface contact. However, a challenge is dealing with the unknown initial magnetic state of the pipe.

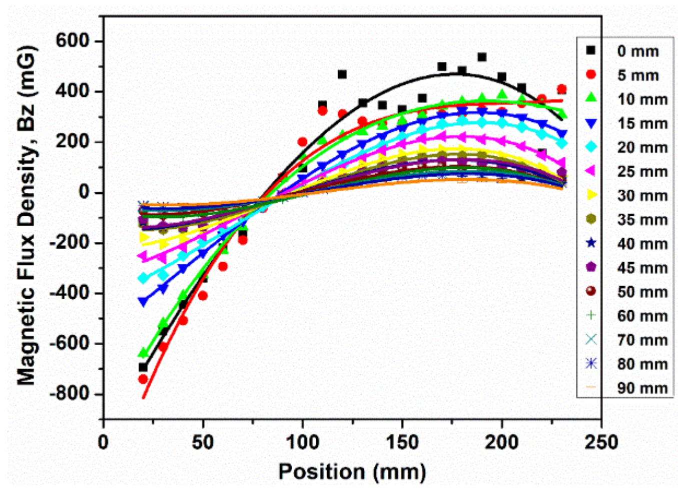

FIGURE 1: MAGNETIC FLUX DENSITY (Bz) AS A FUNCTION OF POSITION ON THE BENT SAMPLE 1 AT DIFFERENT LIFTOFFS. THE SOLID LINES REPRESENT 3RD ORDER FITS TO THE DATA.

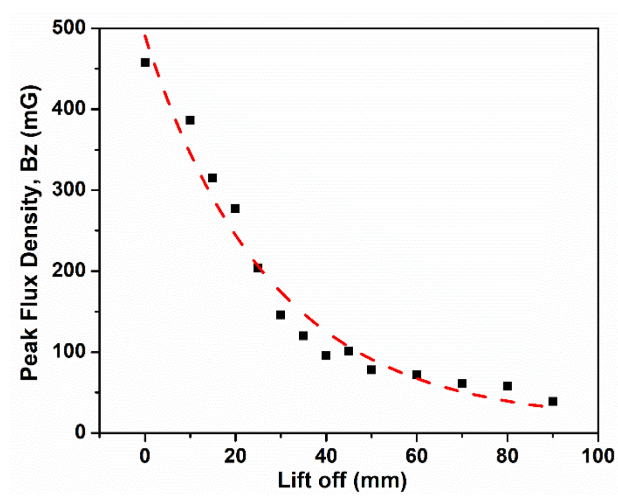

FIGURE 2: MAGNETIC FLUX DENSITY (Bz) AS A FUNCTION OF LIFTOFF FOR THE BENT SAMPLE 1. DASHED CURVE IS AN EXPONENTIAL BEST FIT TO THE DATA.

4. CONCLUSION

The magnetic metal memory method (MMM) is a non-destructive testing (NDT) method with significant potential for pipeline inspection applications. Critical challenges include establishing a quantitative relationship between stress and residual magnetization in the sample, the lack of a complete physical model of the phenomena and dealing with the unknown initial magnetic state of the pipe. The current study was performed to explore the contact/non-contact MMM inspection technology. Bending, which introduced plastic deformation and residual stress, affected the magnetization of various steel samples. An exponential decrease of signal with increase in liftoff was observed.

ACKNOWLEDGEMENTS

This work was sponsored by Pure Technologies through an Ontario Centres of Excellence grant and supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) through the NSERC Engage program.

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