LARGE STAND-OFF MAGNETOMETRY (LSM) FOR BURIED PIPELINE INSPECTION

Experimental study: Influence of dent depth on residual magnetic signal

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Abstract

Dents are among the anomalies which may be a threat to safe operation of pipelines. Dents are characterized by plastic deformation, which causes changes in the magnetic properties of the ferromagnetic pipe wall. Skipper NDT, a company at the forefront of LSM technology, conducted trials to characterize changes in magnetic properties around dents. The objective of the study was to improve the value of the results of the LSM inspections carried out for pipeline operators. Dents with a depth of 5%, 10%, and 15% were indented on X42 pipes of 150 mm (6 inches) diameter, 7 mm wall thickness and 12 m length. Multiple gauges were located around the area of the dents to measure strain during indenting. Mechanical behavior was simulated using the Ansys finite element software to assess accurately the stress distribution around the impacted area and confirm the data recorded using the gauges. Before and after making the dents, magnetic properties were measured using high resolution three-components fluxgate magnetometers at several heights above the pipes on a proprietary test bench developed by Skipper NDT. This paper describes the experimental trials and the results in terms of magneto-mechanical behavior. It is concluded that LSM technology can be used to improve the detection and characterization of dents on pipelines.

I. Introduction

Pipelines are the most effective means of transporting large volumes of oil & gas products. The safe, environmentally responsible operations are always the priority of pipeline operators. To achieve this goal, pipeline operators inspect their pipelines periodically to identify and evaluate any anomalies in the pipe wall.
A novel way to perform these inspections, without contact and thus causing no operational impact, is based on LSM technology. These inspections are run in-line and above-ground. LSM technology is based on established physical principles, namely the Villari effect [1] or the Inverse Magnetostrictive Effect. This principle states that any anomaly generating stress in a ferromagnetic pipe wall generates a change of magnetic induction. Therefore, accurate magnetic measurements above ground along the pipeline combined with advanced signal processing tools enables the detection of anomalies that generate stress in the pipe wall.
For several years, research has been dedicated to solving the complex problem of establishing a fundamental relationship that governs magneto-mechanical coupling [1]–[4].
Skipper NDT offers inspection services using the LSM technology and has been conducting a joint research program with TOTAL for more than 2 years to improve the probability of detection of anomalies on steel pipelines. Skipper NDT has developed a significant expertise in this area through laboratory tests, rigorous research, simulation work and real measurements on buried pipeline networks.
Because dents are among the anomalies affecting pipeline integrity, they are of concern to operators. This type of anomaly is characterized by plastic deformation and strong variation of mechanical stress around the defect [5]–[10]. In the present study, we introduce the first part of the work, conducted on plain smooth dents at the CETIM laboratory in France (Centre des Etudes Techniques des Industries Mécaniques), and report the preliminary results. This work aims to :

- assess the ability to detect dents
- define a relationship between the measured magnetic signal and the type and depth of dent

To perform this experimental work, three procedures were implemented:

- design and construction of a non-magnetic measurement bench
- mechanical modeling by finite element software
- making plain smooth indentations in the middle of 3 pipe joints

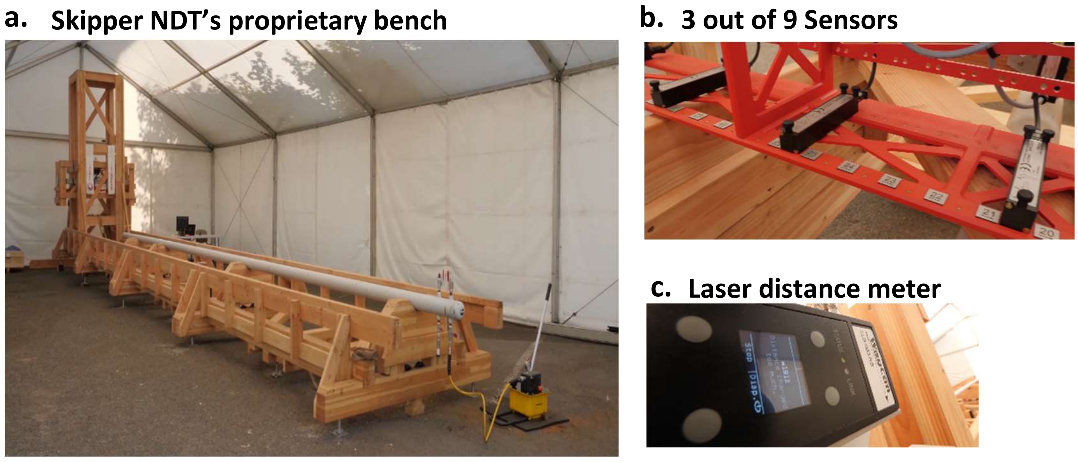
These procedures will be discussed in this paper. The magnetic results obtained will be presented with a detailed analysis, in addition to Skipper NDT's perspective to improve the detection of dents.

II. The non-magnetic test bench

A wooden test bench was designed and built in order to acquire high-resolution magnetic signals from tubular or pipe structures. The bench is composed of a base which supports the pipe to be measured and a tower supporting the magnetic acquisition hardware. The tower is then towed over the 16-metre length of the base to acquire the tube's magnetic signal from beginning to end. The entire bench structure was built with materials free of magnetic interference (no metal). Several parameters can be tested, such as:

- Standoff: the distance between the magnetic sensors and the upper surface of the pipe can vary from 250 mm to 2,500 mm with 50 mm intervals
- Position of the defect: the pipe can be rotated around its axis to measure the defect in different axial positions
- Size of the pipe: the bench can host pipes up to 14-metres long with diameters ranging from 100 to 500 mm (4 to 20 inches).

Figure 1. Non-Magnetic test bench



The tower mounted on the bench houses a purpose-built magnetic recording device that has a resolution higher than 1 nT with an acquisition frequency of up to 2,000 Hz. The following combination of instruments was assembled in order to provide the necessary measurement precision:

- 9 high-precision three-components fluxgate magnetometers, the configuration of which can be changed if needed (Figure 1b), 25 cm horizontal spacing.
- 2 lasers distance meters (vertical and horizontal): one to read the distance from the end of the pipe and the other to measure the exact height relative to the upper surface of the pipe. This allows for high spatial resolution of the data acquired (Figure 1c),
- A datalogger to record and synchronize the data.

III. Preparation of plain smooth dents in pipe

Indenting the pipe was entrusted by Skipper NDT to the CETIM team, specialized in the mechanical field.

Plain smooth dents were chosen to avoid any magnetic effect (such as thickness reduction in curvature) other than the effects of deformation and stress. Seamless joints were chosen to avoid any magnetic effect of welding. Three depths of dents were selected: 5%, 10% and 15% of the outside diameter.

1. Experimental joints

The mass and size of joints to be handled in the laboratory were limited, so the characteristics of the 3 joints were

- diameter: 168.3 mm,
- wall thickness: 7 mm,
- grade: X42 (API 5L),
- length: 10 m,
- seamless.

A tensile test according to the standard NF EN 2002-001 (2006) was performed on a sample taken from the end of each joint (identified 20, 21 and 22) to measure the actual mechanical properties, such as the elastic limit and the Young's modulus.

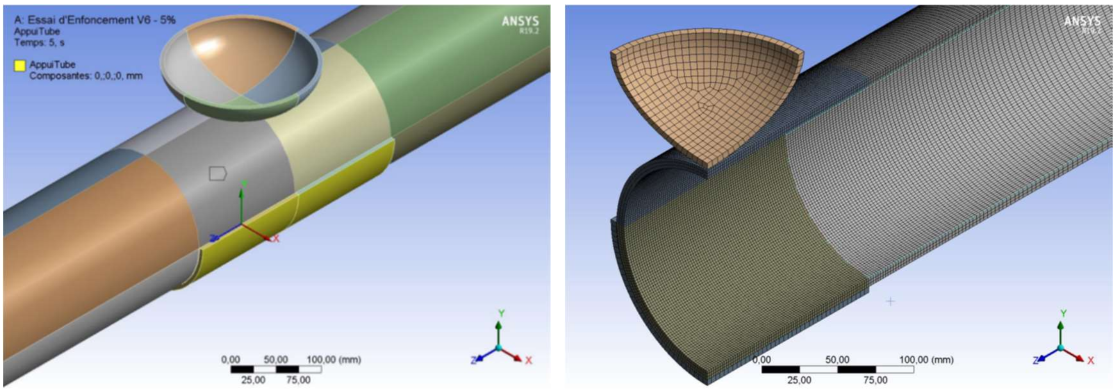
2. Preliminary mechanical simulation

For control of the mechanical test, it was imperative to begin a simulation study. This modeling allowed control of certain parameters, such as:

- the level of stress to be applied to achieve the 5, 10 and 15 % dent depth,
- placement of each strain gauge in areas where the mechanical stress does not exceed its limit so as not to degrade it,
- the distribution (on the surface and in the through-wall direction) of stress in each dent.

The CETIM team used the Ansys software for mechanical modeling (Figure 2-3).
The indenter was modeled in an ellipsoidal shape with half-axes of 90 mm and 50 mm.
To avoid excessive bending of the pipe due to its own weight, it was supported by six planks, placed at intervals of about 2,000 mm (Figure 4).
The stress-strain curves obtained in the tensile tests were used for mechanical simulation.

Figure 2. Mechanical simulation



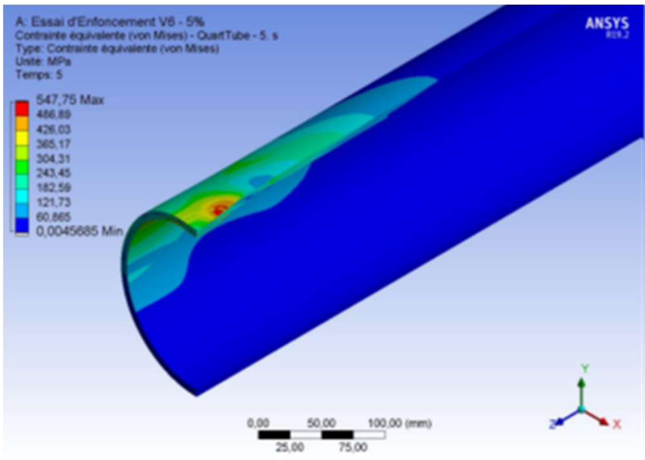
The depression of the tube by the indenter was realized by applying a vertical displacement imposed on the inner face of the indenter (Figure 2). Three displacement values were applied, -9 mm, -17.4 mm and -25.7 mm, in order to generate dent depths of 5%, 10 % and 15%, respectively, of the outer diameter of the tube.
In Figure 3, the equivalent mechanical stress of Von Mises is represented.
These plots show the enlargement of the plastic zone ($\sigma > 320\ MPa$) with increasing depth of the dent.

Stress does not increase linearly with the depth of dent, but a complex distribution of stress is generated within the impact section.

It will be difficult to define a direct relationship between a single stress value and the magnetic field that is measured. The field induced by the material is the result of stress distribution in a section.

Figure 3. Von Mises equivalent stress a. 5% b. 10% c.15%

a.



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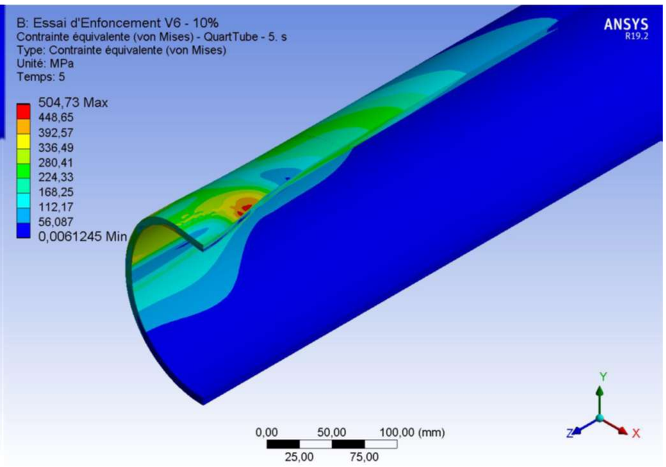
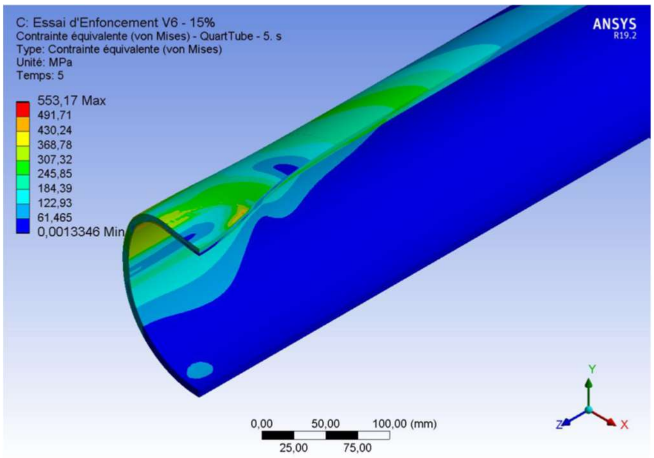


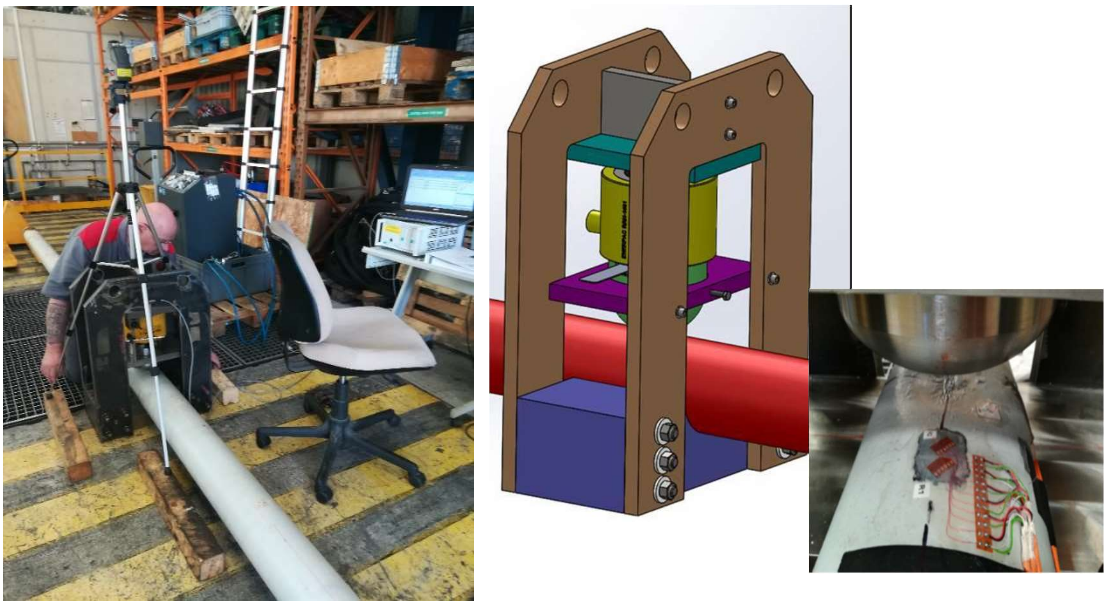
c.



3. Dent: mechanical experiment

A flexion bench has been specially designed for these tests. The bench contains a joint support which makes it possible to limit the friction and the sliding of the joint under the effect of the press. The force applied to the joint is generated by a hydraulic jack.

Figure 4. Mechanical flexion bench



Three triaxial gauges were placed near the impact zone of the indenter. During the test, the indenter displacement and the different components of the 3 gauges (Ra, Rb and Rc) were recorded (Figure 5).

Figure 5. Dent with depth of 15%

In Table 1, the maximum values of strain measured by the 2 gauges (R1, R2) located on the upper surface of the joints and the values obtained by simulation on the same section for each level of depth are listed.

Table 1. Max values of strain ε (%) measured values (gauge measurements) / simulated values

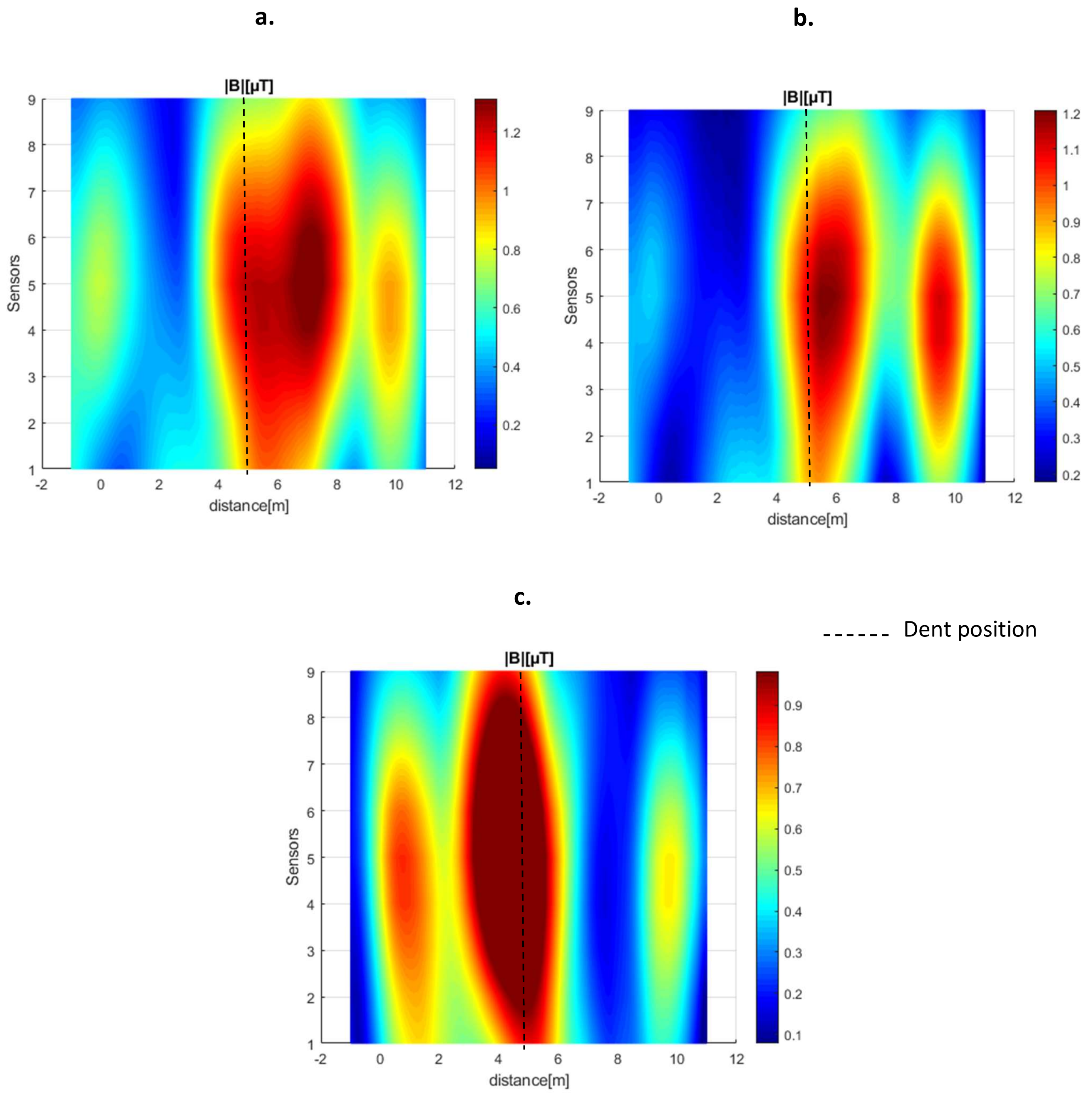
	5%		10%		15%	
	Sim	Exp	Sim	Exp	Sim	Exp
R1	1.47 %	1.5 %	1.50 %	1.53 %	1.51 %	1.6 %
R2	2.51%	2.2 %	2.47 %	2.3 %	2.54 %	2.25 %

The gauge R3 is positioned on the section which undergoes ovality during the test. In this section, there is a sudden variation of the stress during the test on the three tubes. For this reason, the measurements of this gauge are not considered. Measurements of the two gauges R1 and R2 show agreement between the experimental results and the simulation results.
The dents generated by this type of indenting are relatively soft (very high radius of curvature). It should be noted that there is an infinite number of shapes of dents. The appropriate method to classify the dents by family will be the subject of another study.

IV. Results

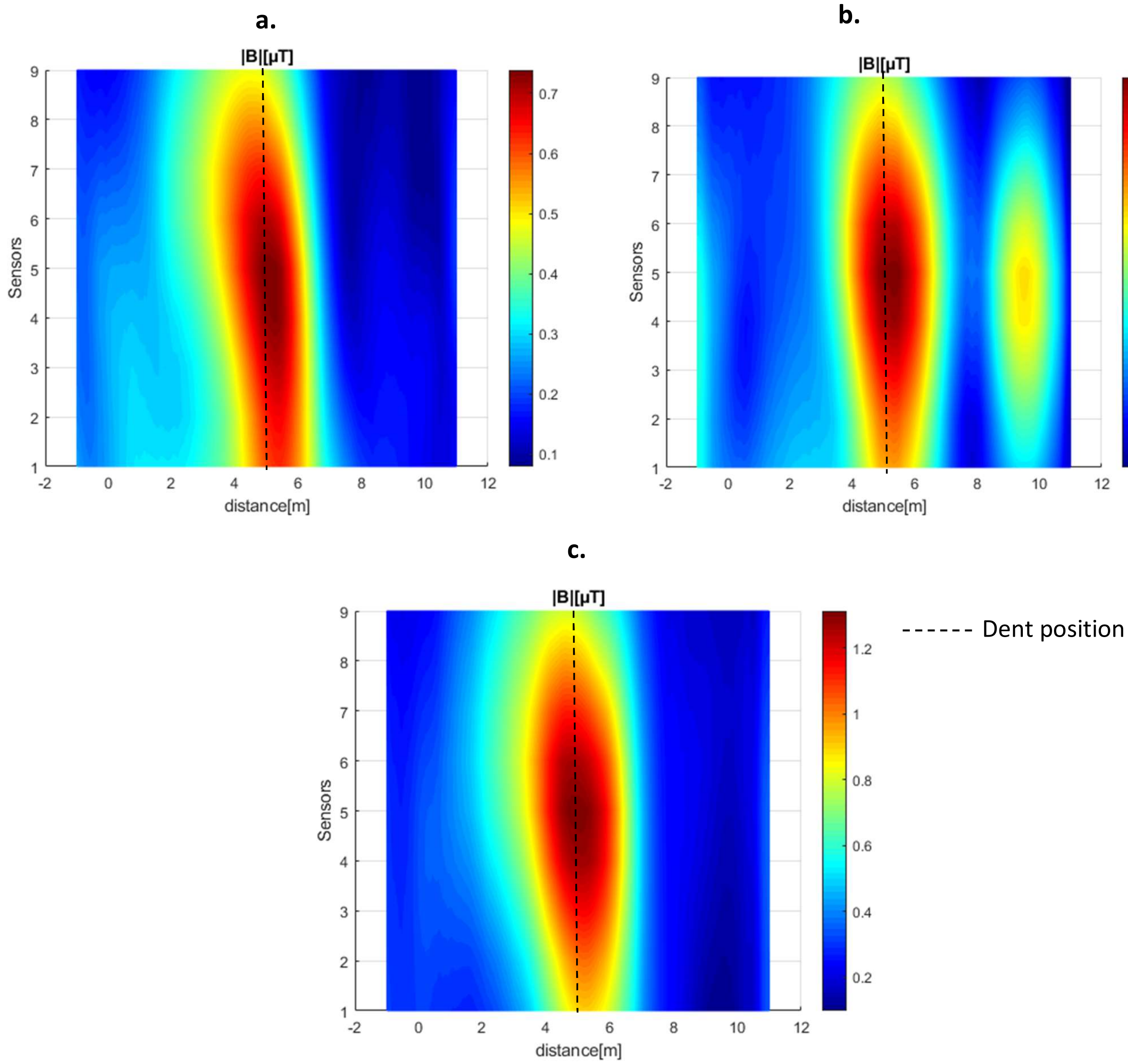
In order to record the initial magnetic state of the three pipes selected for denting, magnetic measurements were previously made at a height of 90 cm.
After the introduction of the anomalies, the pipes were measured again while maintaining the same position as during the first magnetic scan (initial state); i.e., the same upper surface and the same extremity of the pipe at the laser position 0 as in the first measurement.
The introduction of the dents on the three pipes caused a clear and visible change in their magnetic response at 900 mm (Figure 6).
The intensities of the magnetic field are not homogeneous between the three plots, mainly because the magnetization varies from one pipe to another.
The inhomogeneity of the magnetization along the pipe causes the maximum of the magnetic anomaly to be located not exactly at the point of the defect and also causes other peaks to appear.
In order to highlight the effect of the dent, the color bar is fixed at the maximum field intensity of the initial state (without dent). Therefore, we can highlight through a darker color the section which exceeds this reference value of the initial state.
It is, hence, possible to detect the presence of the anomaly on the raw signal even with a 5% dent depth. It is important to note in these graphs that the magnetic impact (amplitude and extent of the magnetic signal) of the dent increases with increased depth of the dent.
The comparison of the magnetic results before and after the introduction of the dent makes it possible to isolate the magnetic change caused by the defect in the pipe.

Figure 6. Intensity of the magnetic field induced by the tubes with dent a. 5% b. 10% c.15%. Sensor spacing is 25 cm



A relative analysis (difference between intensities of magnetic fields before and after the introduction of the dents) made it possible to extract the magnetic variation caused by the defect. This analysis allows elimination of the fluctuations due to the variation in magnetization. Furthermore, it highlights an important observation: the magnetic response of the dent with increasing dent depth.
The intensities of the variation of the magnetic field are 0.74 µT for 5% and 1.03 µT for 10% and around 1.31 µT for 15%, the sensors being 25 cm above the pipe. The increase of the magnetic signal as a function of the depth of the dent makes it possible to associate a magnetic signal with a type of defect (Figure 7).

Figure 7. Difference of the intensity of the magnetic fields induced by the tubes (with dent – initial state) a. 5% b. 10% c.15%%. Sensor spacing is 25 cm



These observations are of great importance for the deployment of LSM technology. Indeed, dents create a strong variation of the local remnant magnetization. The shape of the resulting magnetic signal depends mainly on the extent of the section affected by this change of magnetization, as well as the increase of magnetization generated by the dent.

V. Discussion

A dent is an irreversible plastic deformation of material. Dents cause variations up to the nominal mechanical stress $(\sigma > 320\,MPa)$ over a large section as shown previously in the finite element simulations. This modification of the mechanical properties (in elastic and plastic domains) leads to a modification of the magnetic properties. The results of the experiments reported in this paper make it possible to evaluate the evolution of the magnetic signal for a single type of dent as a function of the depth of dent.
Magneto-mechanical coupling in the elastic and plastic domains remains to be established.
The relationship between the magnetic properties of steel and its mechanical properties is governed by a complex law. Moreover, the existence of a fundamental law in physics that could characterize this coupling is still unknown.
Several previous studies have been conducted to solve this uncertainty. The best-known model is the Jiles-Atherton model [2], which links a uniaxial stress variation to a variation of magnetization in the same direction. This model is, however, limited to the uniaxial case and to the elastic field. It cannot be applied to the case of stress around a dent, which is multiaxial and goes well beyond the elastic limit.
This experimental work was accompanied by a magneto-mechanical characterization study, which will be published elsewhere soon.
Skipper NDT has developed a signal processing algorithm chain to locate specific events on the pipeline such as welds, repairs, thickness changes, etc. It also makes possible to detect signal variations due to dents. The relation between the form/depth of the dent and the shape of the resulting magnetic signal reinforces the possibility of locating a dent and characterizing the type of dent in buried pipelines. The characterization process will be realized primarily through a machine learning algorithm and a library of magnetic signals corresponding to a multitude of configurations.

VI. Conclusions

Dents are anomalies that could expose pipelines to high risk.
This paper has highlighted the interest of using the LSM technology to detect this type of anomaly, which sometimes proves to be difficult to detect through active methods.
Generating dents with the same indenter at an increasing depth showed that the magnetic signal resulting from this type of anomaly increases with the depth of the dent.
This has also shown the lack of a linear relationship between the measured magnetic field and the mechanical stress in the metal. The magnetic signal depends mainly on the shape and extent of the anomaly.

A knowledge of the stress / magnetization relationship is very important in order to carry out simulation work and to generate the library of data necessary for the interpretation of the measured signals. Skipper NDT has carried out characterization work on test samples from pipe, in the elastic domain and then in the plastic domain in order to quantify the variation of the magnetization as a function of the mechanical properties (stress and strain). This magneto-mechanical behavior law is used to convert multiaxial stress distribution into remanence magnetization distribution essential to magnetic simulation. A 3D magnetic model entirely developed by the Skipper NDT team makes it possible to simulate several configurations and to understand several phenomena.
The simulation results corresponding to the experimental tests presented in this paper will be presented in a separate publication.

VII. Acknowledgment

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VIII. References

[1] R. M. Bozorth and H. J. Williams, "Effect of small stresses on magnetic properties," *Rev. Mod. Phys.*, 1945.

[2] D. C. Jiles and D. L. Atherton, "Theory sf the magnetisation process in ferromagnets and its application to the magnetomechanical effect," *J. PHYS. D APPL. PHYS*, vol. 17, pp. 1265–1281, 1984.

[3] M. J. Sablik *et al.*, "Coupled Magnetoelastic Theory of Magnetic and Magnetostrictive Hysteresis," *J. Appl. Phys.*, vol. 32, no. 10, pp. 8480–8482, 1993.

[4] A. Seeger, H. Kronmüller, H. Rieger, and H. Träuble, "Effect of Lattice Defects on the Magnetization Curve of Ferromagnets," *J. Appl. Phys.*, vol. 740, 1964.

[5] A. Cosham and P. Hopkins, "THE PIPELINE DEFECT ASSESSMENT MANUAL (PDAM)," 2004.

[6] J. D. Bhakhar, "THE EFFECT OF DENT UNDER FATIGUE LOADING IN PRESSURIZED," 2015.

[7] I. V. Orynyak and L. S. Shlapak, "Estimation of ultimate pressure for a pipe with a dent," *Probl. Prochnosti*, 2001.

[8] J. H. Liu and A. Francis, "Theoretical analysis of local indentation on pressured pipes," vol. 81, pp. 931–939, 2004.

[9] T. H. Hyde, R. Luo, and A. A. Becker, "Elastic-plastic analysis of offset indentations on unpressurised pipes," *Int. J. Solids Struct.*, 2007.

[10] D. B. Noronha, R. R. Martins, B. P. Jacob, and E. de Souza, "Procedures for the strain based assessment of pipeline dents," *Int. J. Press. Vessel. Pip.*, 2010.