ADVANCED POSSIBILITIES FOR CORROSION INSPECTION OF GAS PIPELINES USING EMAT TECHNOLOGY

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Abstract

Pipelines are considered to be the safest way for transportation of large amounts of liquid and gas over large distances. In the course of the lifetime of a pipeline, however, many reasons can lead to damages affecting the integrity of the line, e.g. manufacturing-related anomalies, operationally induced anomalies or third-party damage. In order to avoid pipeline failures with potentially catastrophic consequences so-called intelligent pigs (or smart pigs) were developed during the last decades: These tools allow for the internal inspection (**In**-**L**ine **I**nspection, ILI) of pipelines using non-destructive testing technologies for the early detection and sizing of defects. Most common are **m**agnetic **f**lux **l**eakage (MFL) and ultrasonic techniques (UT) for corrosion inspection and the latter also for crack inspection. While the ultrasonic techniques offer superior sizing capabilities they are limited to the inspection of liquid pipelines where the medium itself provides the necessary coupling between the (piezoelectric) ultrasonic transducers and the pipe wall. However, this limitation can be overcome by recent developments using EMAT (**E**lectro-**M**agnetic **A**coustic **T**ransducer) technology. By a special sensor design, the EMAT inspection is combined with **e**ddy **c**urrent (EC) inspection and MFL inspection at the same time. As a result, this new multi-technology approach offers improved sizing as well as enhanced feature identification for wall thickness inspection of gas pipelines.

1 Introduction

Pipelines are one of the cornerstones of modern civilization constituting an essential part of the infrastructure. More than 3 million kilometers of pipelines connect the reservoirs of oil and gas, the ports of shipment, the refineries and the storage facilities today. Non-destructive testing of the pipeline system by means of in-line inspection using intelligent pigs has become an important part of this system in ensuring its safe and economic operation. When looking back at the history of intelligent pigging from the early 1970s until today, the following trends can be observed:

- simple applications (e.g. geometry tools) towards more complex applications (e.g. crack inspection),
- low resolution scanning grid (e.g. 30 mm x 10 mm) towards higher resolution scanning grid (e.g. 5 mm x 1 mm),

- one tool for one task (e.g. corrosion inspection) towards one tool for several tasks (e.g. corrosion & crack inspection) performed simultaneously,
- one tool providing one inspection method (e.g. ultrasonics) towards one tool providing several methods (e.g. ultrasonics, MFL) performed at the same time.

This progress is, of course, directly related to parallel developments in other fields like:

- miniaturization of electronic circuits,
- increase of computing power / data processing speed,
- increase of data storage capacity,
- advanced development tools (software development, CAD etc.),

that all have a strong impact on the improvement of inline inspection tools [1].

Apart from giving some general information on inline inspection, this paper is focusing on one of the recent developments combining several independent non-destructive inspection methods in one tool (LineExplorer® 3T-tool) to be used for the inspection of gas pipelines.

2 Objective of In-Line Inspection

Even though pipelines provide a high level of safety for transportation of gas, oil and products, there is a variety of reasons that may cause defects in the pipe wall eventually leading to (potentially catastrophic) pipeline failure during operation. The main types of defects can be categorized as:

- **Deformations** (dents, ripples, wrinkles, buckles or similar): Deformations often occur during laying of the pipe, e.g. when the pipe is laid on stony ground (rock dents). Other reasons can be interference with agricultural equipment, landslide or similar (see example in Figure 2.1).
- **Metal Loss:** One of the main reasons for metal loss are corrosion processes which may take place on either side of the pipe wall. Internal corrosion is mainly related to aggressive ingredients of the medium; external corrosion (see example in Figure 2.2) often takes place at locations with coating damages and corrosive soil conditions. Other reasons for metal loss are grinding, erosion, wall thickness variations in seamless pipe etc. Corrosion growth rates are typically below 1 mm/year but can amount to several mm/year under special circumstances. Corrosion defects normally lead to failure by leak.
- **Cracks:** According to the loading conditions in pipelines the main stress component is the hoop stress acting in the circumferential direction. Therefore, the majority of cracks that develop in pipelines have an axial orientation. In most cases, cracks (or crack-like defects) can be

associated with manufacturing-related defects in or at the longitudinal weld such as hot cracks, lack-of-fusion or similar. Existing cracks may grow during operation, for example, by fatigue mechanisms. Another type of cracks encountered in pipelines is SCC (stress corrosion cracking) which often develops in the form of crack colonies (see example in Figure 2.3). These cracks result from an adverse combination of stress level, material susceptibility and chemical properties of the ambient soil. Crack-like defects normally lead to failure by rupture if the critical crack size is reached.

Figure 2.1: Example of deformation damage (wrinkle probably caused by landslide)

Figure 2.2: Example of external corrosion damage

Figure 2.3: Example of an SCC colony

In order to prevent pipeline failure, any defect that may become critical has to be detected early enough. As most of the pipelines are buried and also covered by a protective coating, a complete inspection can only be done from the inside. This is achieved with in-line inspection using automated inspection systems called intelligent pigs (or smart pigs). The ultimate goal of this type of inspection is to detect a certain type of defect with a high POD (**p**robability **o**f **d**etection) and to provide high resolution data that allow precise sizing of the detected defects.

Following the inspection run, a data analysis process takes place yielding a list of all the anomalies found including their type, location and size. Based on these results, defect assessment is usually performed using appropriate standards in order to quantify the severity of the detected defects, thus allowing the pipeline operator to take adequate measures such as repair or replacement of the affected pipe. In case that high-precision data are available from subsequent inspection runs, a run comparison can be carried out yielding defect growth rates that serve as input data for fitness-for-purpose (FFP) studies. The objective of such an FFP study is then – aside from recommending immediate actions – to define strategies that also ensure the future integrity of the inspected pipeline.

3 Inspection Systems (Intelligent Pigs)

Intelligent pigs are automated inspection systems [2] which are usually designed such that one inspection tool is looking for a specific type of defect utilizing one technology. Table 3.1 gives an overview.

Table 3.1: Overview of current ILI tools according to the inspection task

Task	Inspection Tool	Inspection Principle	Comment
Geometry Inspection	Caliper tool	Mechanical deflection	
Metal Loss Inspection	MFL tool	Magnetic flux leakage	liquid & gas lines; indirect measurement
	Ultrasonic tool	Wall thickness measurement (piezoelectric)	requires liquid coupling; direct measurement
Crack Inspection	Ultrasonic tool	45°shear wave (piezoelectric)	requires liquid coupling; axial & circumferential
		EMAT guided waves	field testing stage

More and more, inspection tools also contain so-called INS-units (Inertial Navigation System) that measure the pipeline coordinates x,y,z by means of acceleration sensors. After the inspection, the measured coordinates are synchronized with GPS coordinates obtained from aboveground reference points. This procedure allows for a very precise localization of any anomalies that have to be verified later on by excavation.

In order to perform an in-line inspection the inspection tool is launched into the pipeline through a special launching facility and then pumped through the pipeline together with the medium transported. Likewise, the tool is received in a receiving facility at the end of the pipeline.

The design of the (standard) tools has to take into account several requirements with regard to the pipeline construction as well as the environmental conditions. Some typical data are listed in Table 3.2.

Apart from the tool specification, a defect specification has to be set up for every inspection tool. Therein, the type of defects that can be detected, the corresponding minimum defect size and the sizing and localization accuracies are specified including their respective measuring tolerances. Some typical examples are given in Table 3.3 for the different inspection tasks. An example of an ultrasonic inspection tool designed for wall thickness inspection is shown in Figure 3.1.

Table 3.2: Typical testing requirements for an inline inspection

Inspection distance (km)	1 – 500
Axial resolution (mm)	3
Pipeline diameter (Inch)	6 – 56
Minimum bend radius	3 D
Wall thickness (mm)	5 – 25
Operating pressure (bar)	10 – 100
Temperature (°C)	-10 – +50
Inspection speed (m/s)	0.5 – 2

Table 3.3: Typical defect specification for different inspection tasks (excerpt)

Type of tool	Minimum specified anomaly size
Caliper tool	Diameter reduction: 2 % of OD (outer diameter)
MFL corrosion tool	Length: 10 mm Depth: 10 % wt Depth sizing: ± 10 % wt
Ultrasonic wall thickness tool	Length: 10 mm Depth: 0.5 mm Depth sizing: ± 0.5 mm
Ultrasonic crack detection tool	Length: 30 mm Depth: 1 mm

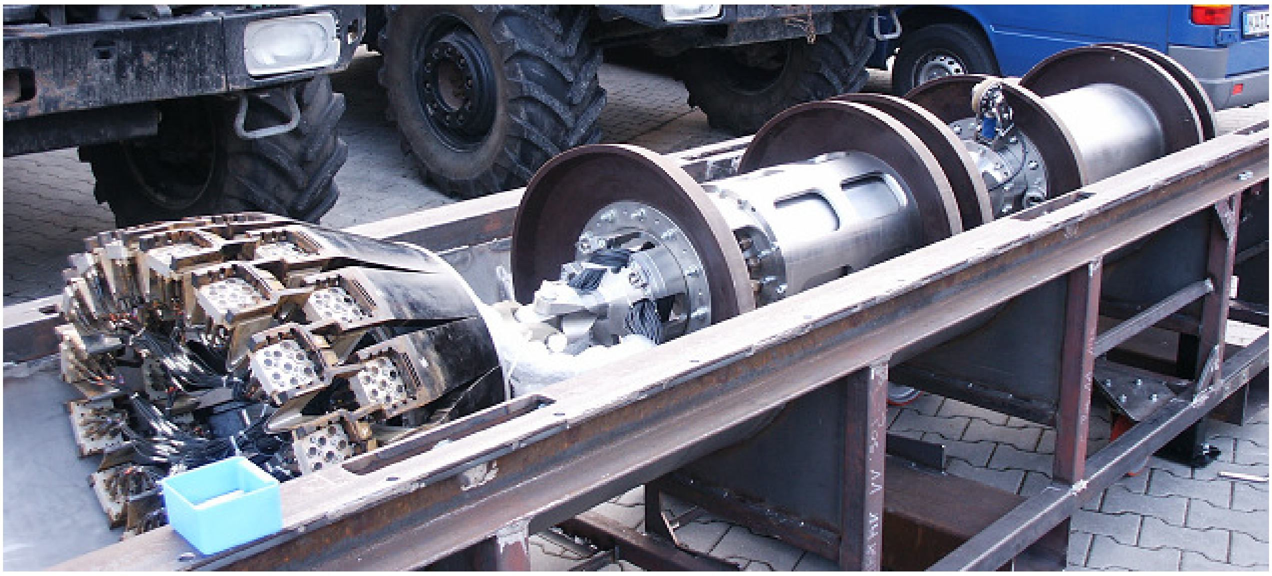


Figure 3.1: Ultrasonic ILI tool for wall thickness inspection (24" design).

4 Multi-Technology Tool for Gas Pipeline Inspection

As compared to MFL the ultrasonic wall thickness measurement is a direct method that provides an absolute measure of the remaining wall thickness and hence the defect depth in case of metal loss. The better accuracy of the ultrasonic method also enables more reliable defect assessment which, in turn, leads to reducing the number of repair excavations after an inspection. However, conventional ultrasonic probes which use the piezoelectric effect, need a liquid coupling medium in order to get enough ultrasonic energy into the pipe wall. Therefore, ultrasonic tools based on this sensor type cannot be used for inspection of gas pipelines unless the tool is operated in a liquid batch [3]. In order to enable an improved wall thickness inspection for gas pipelines a new tool has been developed, that combines the advantages of different, independent non-destructive methods in one tool. In particular, the tool includes the EMAT technology [4,5] for precise ultrasonic wall thickness measurement without the need of a liquid coupling medium.

4.1 Principle

The operation principle of the new tool is based on the EMAT technology [6]. As shown in Figure 4.1, the sensor is located in the center of a magnet bar that generates a tangential magnetic field. The sensor itself contains a transmitter coil and a receiver coil, the design of which is optimized for the current application [7}. Polarized ultrasonic shear waves with a frequency of 2,5 MHz are generated using the magnetostrictive effect [4]. The ultrasonic pulses propagate perpendicularly to the pipe wall surface. From the time-of-flight of the back-wall echo and known ultrasonic velocity in pipe steel, the (remaining) wall thickness is readily obtained.

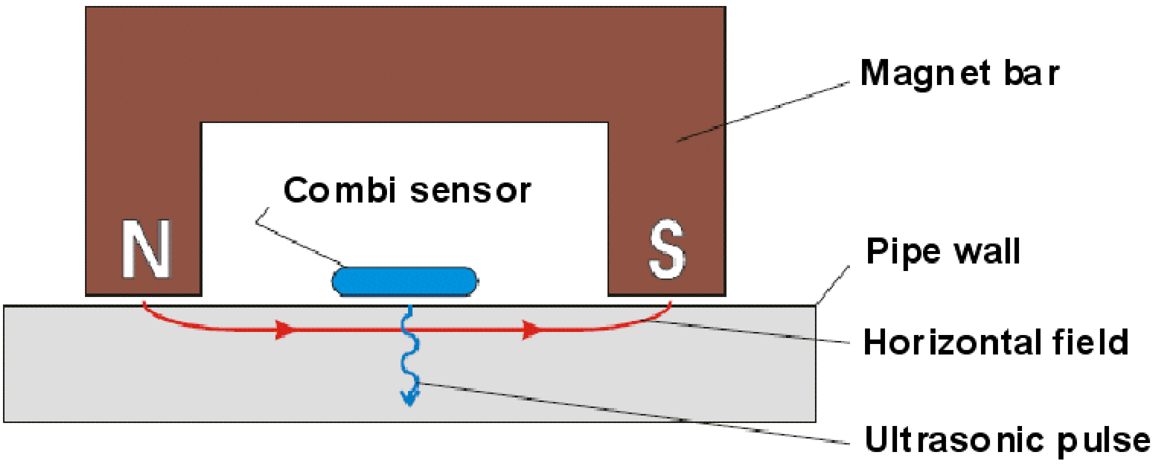


Figure 4.1: Measuring arrangement for generating EMAT based ultrasound.

Taking advantage of the fact that the EMAT principle is based on coils, these coils can also be used to pick up the MFL signal generated by electromagnetic induction of the stray-flux field in the moving coil. The MFL information is then easily separated from the ultrasonic signal by suitable frequency filtering and time gating.

Furthermore, the EMAT sending pulse generates a pulsed eddy current signal in a separated coil. The height of this signal depends on the liftoff of the coil (see Figure 4.2). This information can be used, for example, to measure the depth of internal corrosion defects.

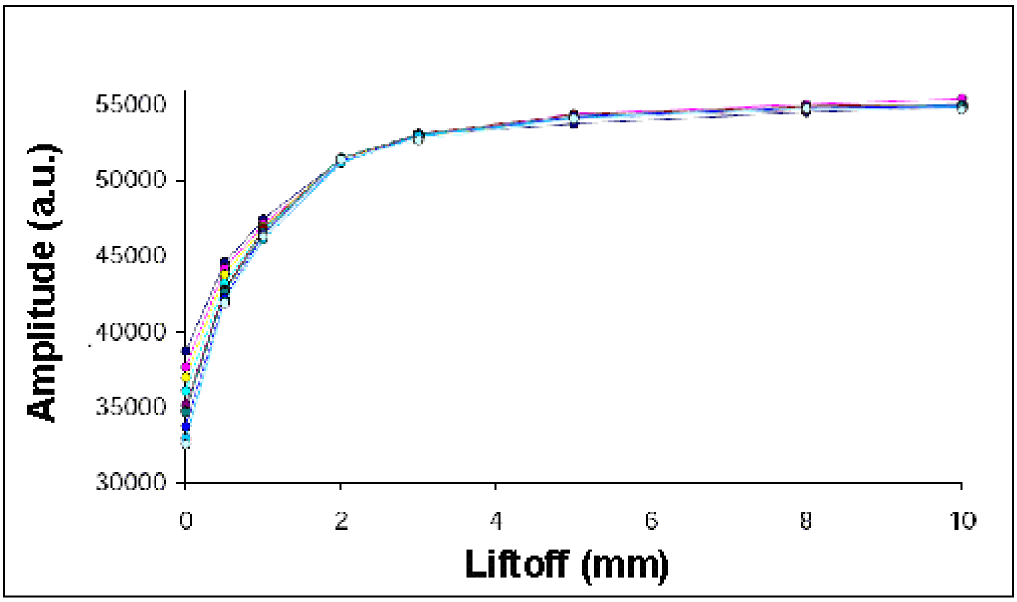
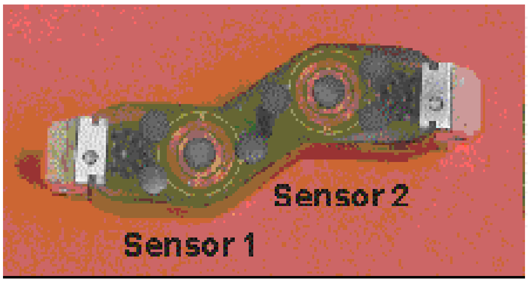


Figure 4.2: Dependency of the EC amplitude on the coil liftoff. For liftoffs > approx. 7 mm the amplitude shows a saturation behavior.

4.2 Sensor Design

The EMAT coils (sending and receiving) and the EC coil are set-up in a concentric manner with a maximum outer diameter of 10 mm (Figure 4.3). One basic unit contains two sensors. These units are wear-protected by a ceramic layer. Ten basic units are integrated into one larger unit providing a flexible suspension of the basic units so that the sensors can follow the internal surface of the pipe wall (Figure 4.3).



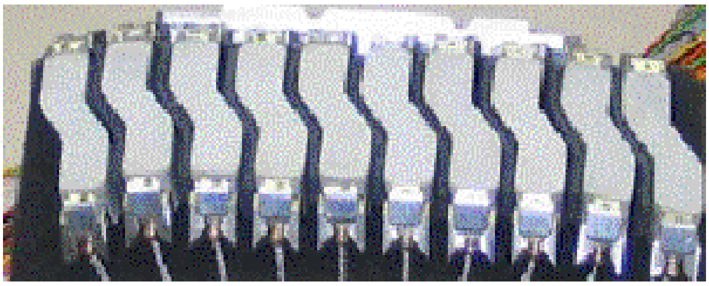


Figure 4.3: Left: basic unit containing two sensors (shown without wear plate). Right: unit with 20 basic units with ceramic wear protection. Each sensor measures ultrasonic (EMAT), MFL and EC signals.

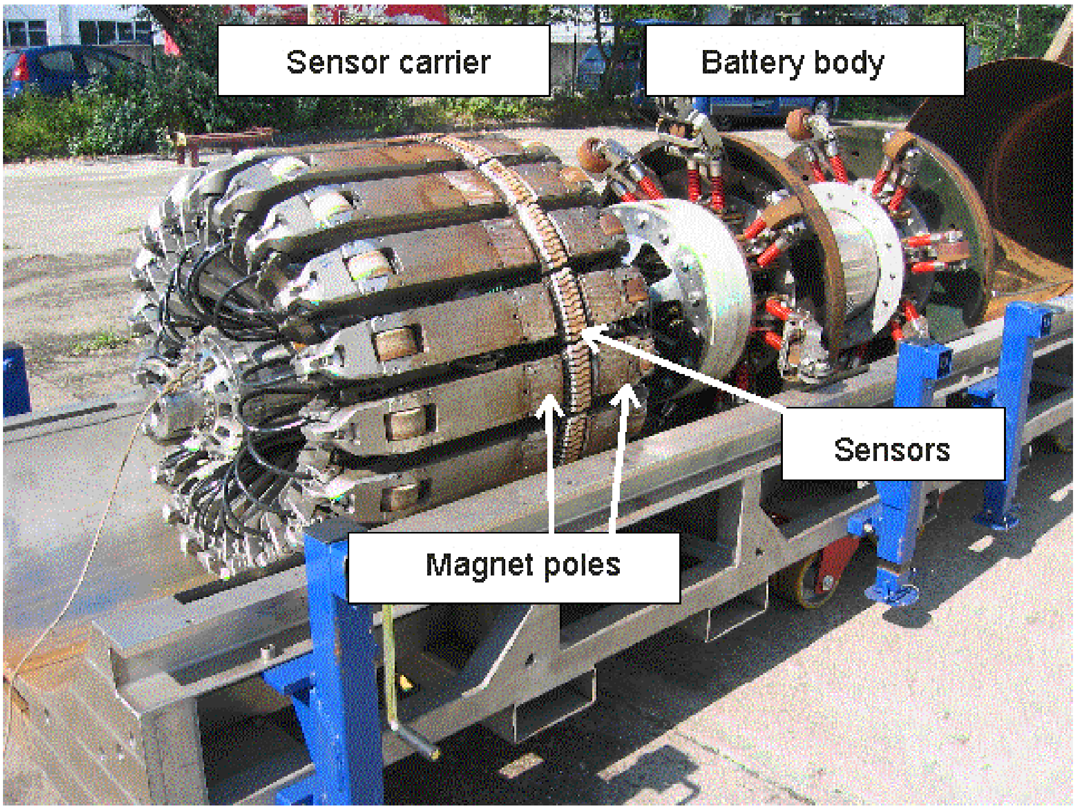


Figure 4.4: LineExplorer 3T-tool during launching. The 40" version contains 400 sensors.

4.3 Tool Setup

The new tool (LineExplorer 3T-tool) is configured for a pipeline diameter of 40" (Figure 4.4). Due to a modular design of the basic components it can be easily adapted to other diameters.

The wheel-supported sensor carrier contains 20 magnet bars mounted into guiding skids. The EMAT electronic units are located close to the sensors behind the skids; each unit can drive up to 20 channels (sensors). The current tool is equipped with 400 sensors providing a circumferential sensor spacing of approx. 8 mm. The front body which is also wheel-supported contains the batteries as well as the data processing and data storage units.

4.4 Test pipeline

In order to validate the performance of the LineExplorer 3T-tool a test pipeline was set up containing a section with over 180 artificial defects (Figure 4.5). About half of the defects are located on either side of the pipe wall (internal, external) covering a variety of shapes and sizes. Some examples are shown in Figure 4.6. The wall thickness of the test spool was 16 mm.

Figure 4.5: 40" test pipeline (top) containing test spool with artificial defects (bottom)

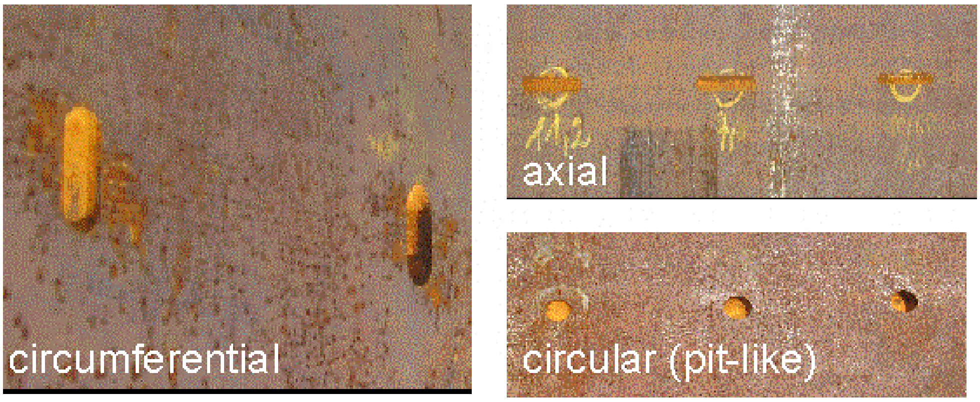


Figure 4.6: Examples of artificial defects with different shapes

4.5 Results

Figure 4.7 shows C-scans of a section of the test spool as obtained with the different inspection methods. With MFL (middle of Figure 4.7) all defects are detected. With EC, all the internal defects are detected (bottom of Figure 4.7). There are also some indications from the external defects which are, however, quite weak and which show a different signal pattern. Apart from some defects with sizes below 10 mm, the EMAT method detects all defects with lengths ≥ 10 mm. Here, the internal defects lead to echo loss (green color) as the back-wall signal is vanishing for liftoffs > 1 mm.

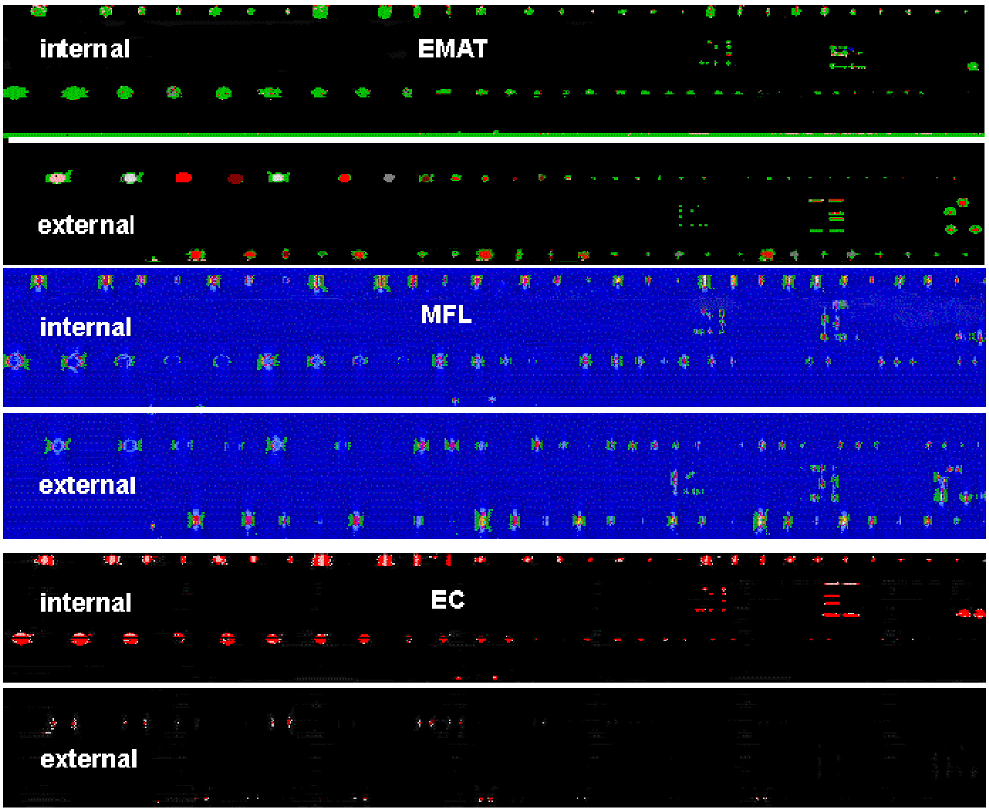


Figure 4.7: C-scans from test section: top: EMAT result; middle: MFL results; bottom: EC result; the white line in the center of the C-scans separates the internal and the external defects.

Figure 4.8 shows a result for a single external defect. Here, the depth can directly be measured from the EMAT B-scan yielding the correct value of 4 mm. As expected for external metal loss there is almost no EC-signal. Only for the deeper defects some minor indications are visible probably related to changes in the magnetic permeability. The MFL-signal shows the radial component of the stray-flux field. It exhibits a very sharp gradient at the edges of the defect thus allowing for a very precise length measurement.

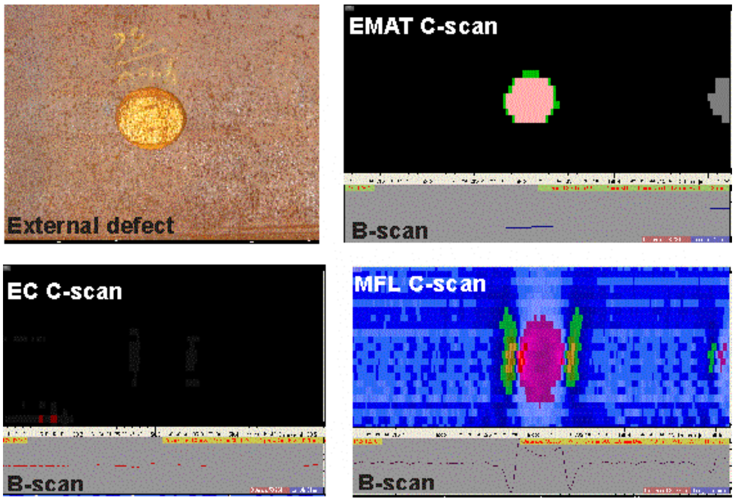


Figure 4.8: C- and B-scans from an external circular defect (diameter: 30 mm, depth: 4 mm)

An example for internal defects is given in Figure 4.9 showing three adjacent circular defects. In this case, the correct depths are obtained from the EC-signal which can be confirmed using the MFL-signal. Due to the sensor liftoff the EMAT-signal, however, is lost, i.e., the defect area shows up as echo loss (green color).

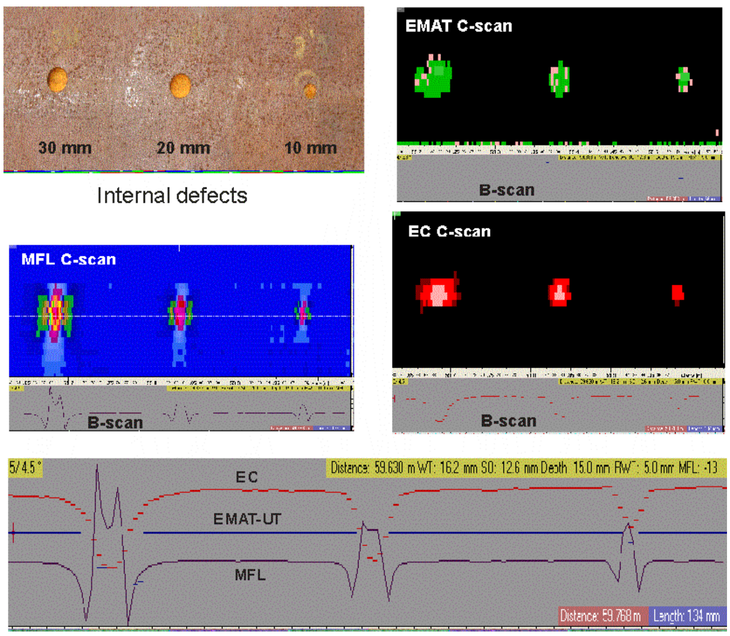


Figure 4.9: C-scans from a group of three internal defects (bottom: B-scans along the center of the defects).

Another example refers to narrow axial corrosion. Such anomalies cause some problems for MFL as only the edges of the defects produce sufficient signal (see Figure 4.10). Then the indication may be interpreted as two single defects instead of one long defect. Including the information of the EC indication the correct result is readily obtained as can be seen in Figure 4.10.

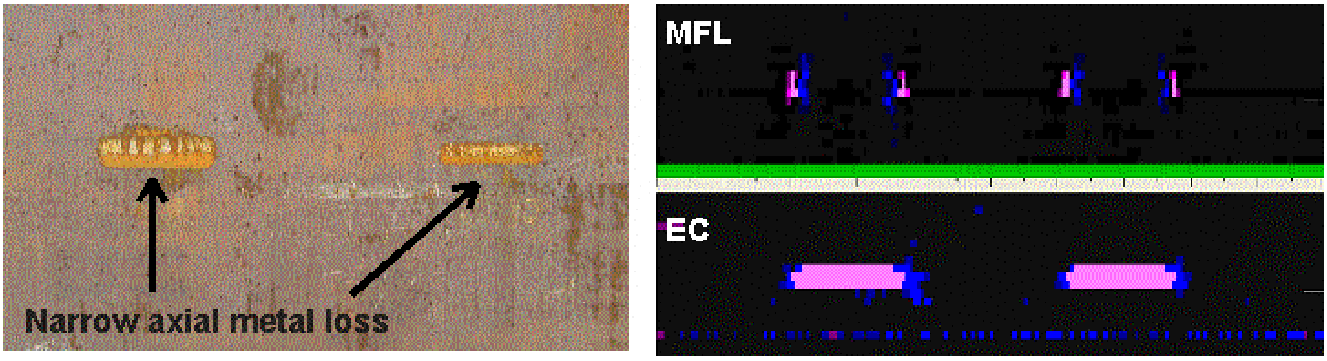


Figure 4.10: C-scans (right) showing MFL- and EC-signals as obtained from internal narrow axial metal loss

A further example demonstrates the axial & lateral resolution of the different methods as shown in Figure 4.11. The C-scans as obtained from a group of nine internal defects having axial as well as circumferential distances between 10 mm and 40 mm reveal that EMAT and EC allow for a clear separation of the individual defects. The broader MFL signals, however, are interfering for distances < 20 mm which makes it difficult, especially for the circumferential direction, to resolve the individual indications.

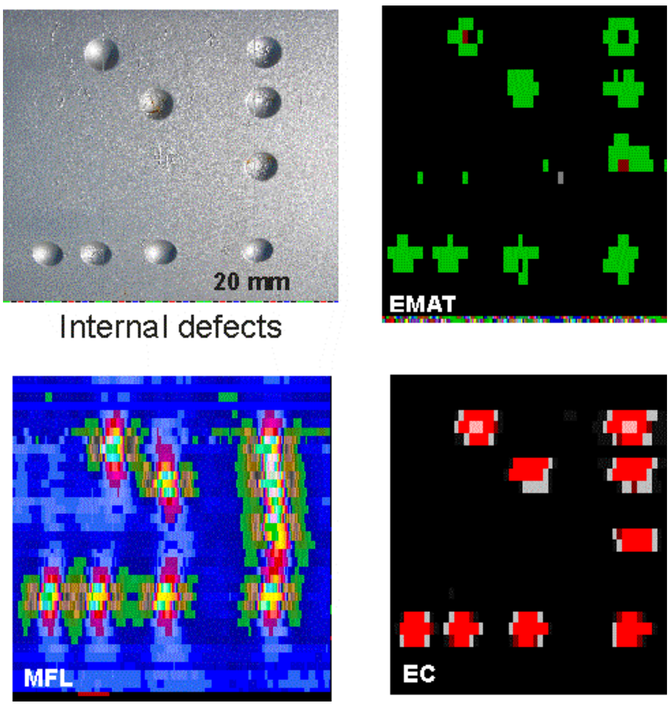


Figure 4.11: C-scans from a group of internal defects demonstrating the the axial/lateral resolution of the three methods

To demonstrate the sizing capabilities of the new tool, some results are shown in Figure 4.12 and Figure 4.13. In Figure 4.12 the depths as determined from the EMAT data are compared to the manufacturing data for the external defects with lengths ≥ 20 mm. Here, the standard deviation for depth measurement of ± 0.5 mm (± 3.1 % with regard to the wall thickness of 16 mm) is in accordance with the specification. Similarly, the standard deviation for the length measurement (as evaluated from the MFL data) amounts to ± 6 mm, being also within the expected range (see Figure 4.12). For sizes < 20 mm the sensor size becomes comparable to the defect size and the accuracy of the depth sizing may be reduced.

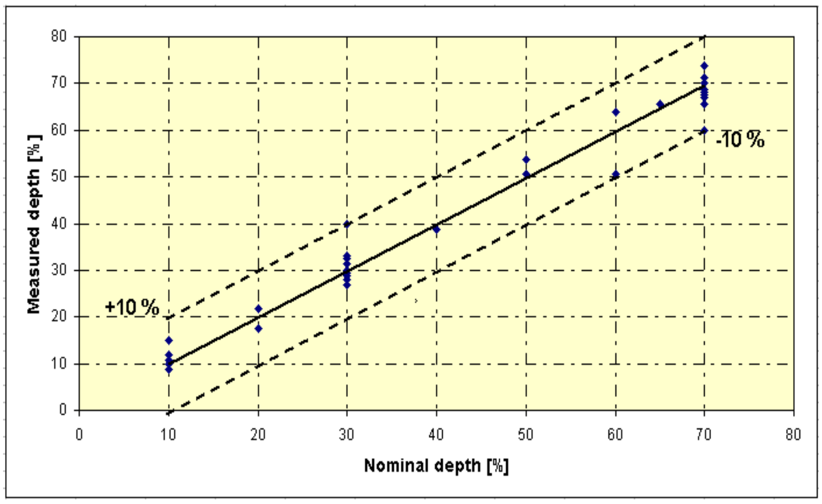


Figure 4.12: Comparison of measured depth from EMAT wall thickness measurement vs. nominal depth (external defects). It should be noted that some data points may refer to more than one measurement.

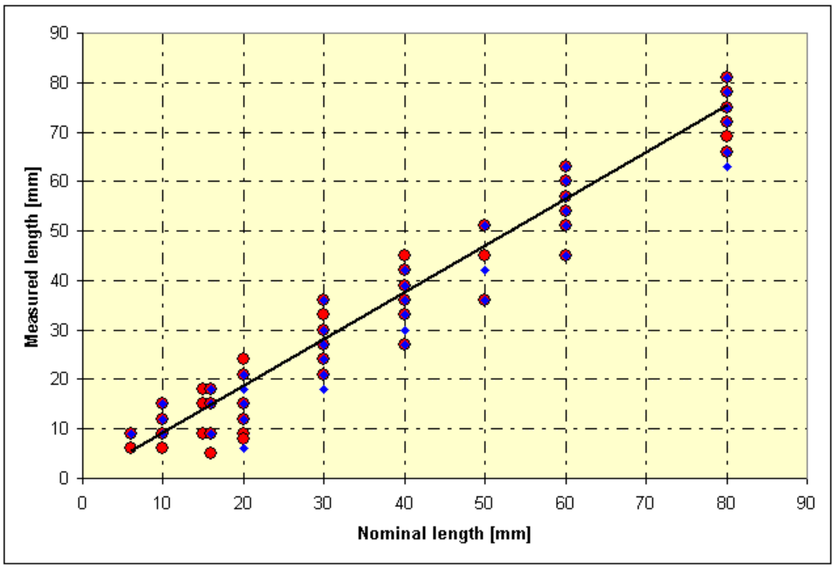


Figure 4.13: Comparison of measured length obtained from the radial MFL component vs. nominal length (**o**: internal defects, ◊ external defects). It should be noted that some data points may refer to more than one measurement.

5 Discussion

The simultaneous use of three independent physical methods (ultrasonics, MFL and EC) as realized in the new LineExplorer 3T tool, offers several advantages compared to standard "single method" tools. The redundancy of the data yields an enhanced probability of detection (POD) and in particular a higher probability of identification (POI). For example, laminations sometimes may produce an ultrasonic signal that looks similar to an external metal loss, whereas MFL and EC will not show a signal response in this case. Then the combined information enables a reliable discrimination for this type of anomaly.

There is also a good potential for improving the defect sizing (length, width, depth) as each quantity can be measured by at least two independent methods (see. Table 5.1). For external defects, the ultrasonic method provides the best accuracy as it measures the remaining wall thickness directly. Algorithms for depth evaluation from the MFL signal are under development. Compared to existing tools we expect some improvements as the actual wall thickness measured by UT can be taken into account. This information is usually not available for standard MFL tools thus reducing the accuracy of depth sizing. Apart from using the MFL signal, the depth of internal metal loss can be determined from the EC signal. Here, calibration curves are required to calculate the depth from the measured EC amplitude (see Figure 4.2).

Table 5.1: Sizing options for metal loss defects showing the redundancy of the new tool.

	Internal Metal Loss		**External Metal Loss**	
METHOD	***Length***	***Depth***	***Length***	***Depth***
EMAT-UT	**indirect**	**/**	**direct**	**direct**
EC	**direct**	**indirect (cal. curve)**	**/**	**/**
MFL	**direct**	**indirect (cal. curve)**	**direct**	**indirect (cal. curve)**

6 Conclusions

The new LineExplorer 3T-tool can be used for advanced inline inspection of gas pipelines. Compared to conventional tools the simultaneous use of three independent non-destructive methods provides

- better probability of detection
- better probability of identification
- improved depth sizing, especially for external metal loss
- a pipe tally with precise wall thickness data for each pipe joint.

Consequently, those improvements will enable pipeline operators to reduce the follow-up costs of an inspection by reducing the number of false calls as well as by providing the type of data that can be used for more accurate defect assessment.

7 References

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