Tool Tolerances in MFL In-Line Inspection and Why They're Needed

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Abstract

While the principle of magnetic flux leakage (MFL) is relatively simple, its application in in-line inspection (ILI) of carbon steel pipe is far more complex. MFL system design and analysis encompass complex interactions between the magnetic field and flux leakage produced by metal loss defects in the pipe wall, making signal identification & interpretation difficult. Thus, the need for tool tolerances.

This paper discusses the cause and effect of wide-ranging factors which influence the reported depths & dimensions of MFL In-line Inspection (ILI) data. Including,

Magnetic strength
Magnetic saturation
Residual magnetism
Pipe Wall Thickness
Velocity
Debris
Compressive and/or Tensile Residual Stress

Our purpose for writing this paper is to educate Pipeline Operators about the complexities of quantifying metal loss defects from MFL ILI tools, and why there are tolerances associated with metal loss sizing from MFL ILI tools, and why sometimes the metal loss sizing prediction falls outside the specified tool tolerance.

Introduction

The Magnetic Flux Leakage (MFL) technique used for nondestructive testing has been around for over 150 years. Cannon barrels were inspected for defects by magnetizing the cannon barrel and then sliding a compass over the barrel to look for movements of the compass's needle [1]. This MFL technique was first used to inspect a pipeline in the 1960's. These early tools were very rudimentary and only had analog sensors and recorder that only covered the bottom quadrant of the pipeline. As the need for assessing the integrity of a pipeline grew, great strides were accomplished in MFL In-line Inspection (ILI) tool development to create the ability to inspect an entire pipeline for metal loss.

British Gas, as a large operator of pipelines, saw the need to have pipeline ILI tools provide information to engineers to perform sentencing calculations. Since these pipeline ILI tools were not available in the market, British Gas set out to develop its own pipeline ILI tools in the 1970's [2], and by the late 1980's had developed high resolution MFL ILI tools. They also developed a sizing specification for sizing metal loss defects. The sizing specification stated that the MFL ILI tools could size the depth of the metal loss defects to +/- 10% of the wall thickness, 80% of the time. This sizing specification has become an industry standard and is still used today with most MFL ILI tools more than 40 years later. While this sizing specification (+/- 10%, 80% of the time) has become the industry standard for MFL ILI tool tolerances, it has been difficult at times for even modern MFL ILI tools to meet this specification.

The goal of this paper is to educate Pipeline Operators about the complexities of quantifying metal loss defects from MFL ILI tools, why there are associated tolerances associated with metal loss sizing from MFL ILI tools, and why the metal loss sizing prediction can fall outside the specified tool tolerance.

How accurate are MFL ILI tools?

ILI vendors with MFL ILI tools will provide pipeline operators a tool specification sheet that will list the metal loss sizing accuracy of the MFL ILI tool. There are typically tolerances associated with depth, length, and width of metal loss features. After an MFL ILI inspection of a pipeline, the pipeline operator will typically go out and investigate or repair metal loss features, and in the process gather physical dimensions of metal loss defect. The physical dimensions of a metal loss defect can then be compared to the dimensions that were predicted by the MFL ILI vendor. With a big enough sample size, some inference can be made to whether the MFL ILI tool met the sizing specification provided by the MFL ILI vendor. This information should be provided back to the MFL ILI vendor so that the MFL ILI tool performance can be evaluated and potentially improved. This information about what was predicted by the MFL ILI tool and what was found and measured in the ditch is typically not shared outside of the pipeline operator and MFL ILI vendor. So, there are islands of MFL ILI performance data sitting with pipeline operators and ILI vendors, but it is hard to know how the sizing performance of MFL ILI tools as an industry are performing.

An interesting study of the sizing performance of ILI tools was conducted by Det Norske Veritas (DNV) in 2016 [3]. In this study, DNV contacted 11 pipeline operators and asked them to provide data comparing ILI reported dimensions to dimensions measured in the field. These 11 pipeline operators provided data on 68-line segments, and over 3000 individual pipeline metal loss defects. The data was collected by the pipeline operators from 2010 to 2015. It is not known if DNV looked at the specified tool tolerance for a particular metal loss defect as the depth tolerance for smaller metal loss defects is often greater than +/- 10%, but it appears all MFL defects were evaluated to the +/- 10% depth tolerance. Here are some interesting findings after DNV analyzed the data.

1. For depth accuracy of MFL ILI tools, 68.6% of defects were within +/- 10% and 83.7% of defects were within +/- 15%
2. The depth accuracy increased between 2010 and 2015. The MFL dataset from 2015 had a depth accuracy with 85.0% of defects within +/- 10%
3. As the predicted depth of the defect increased, so did the error. For defects between 60% and 80% depth, the depth accuracy was 61.3% of defects within +/- 10%.
4. There was a significant dip in accuracy for diameters of pipe 12" and below. The smaller the diameter the more error in the accuracy. For 8" diameter pipe the accuracy was approximately 50% of defects within +/- 10%.

This DNV study exposes some of the weaknesses and limitations of MFL sizing accuracy. With such variation in sizing of metal loss defects, what are pipeline operators to do when the sizing accuracies don't match the vendors sizing specification? Let's examine several factors that affect the MFL signals collected by MFL ILI tools. By understanding these factors, a pipeline operator can be in a better position to have a discussion with the ILI tool provider to ultimately get the most accurate sizing possible.

MFL principles

An MFL ILI tool uses very strong rare earth magnets to induce a magnetic field into the pipe wall. An array of sensors is placed along the inside surface of the pipe wall to measure changes in the magnetic field as the MFL ILI tool travels down the pipeline. Figure 1 shows a cross section of a typical MFL ILI tool's magnet setup against a pipe inner wall with a metal loss defect. Think of an MFL ILI tool's magnet setup as a big "horseshoe" magnet placed up against the pipe wall with the backing bar providing magnetic flow between the magnets.

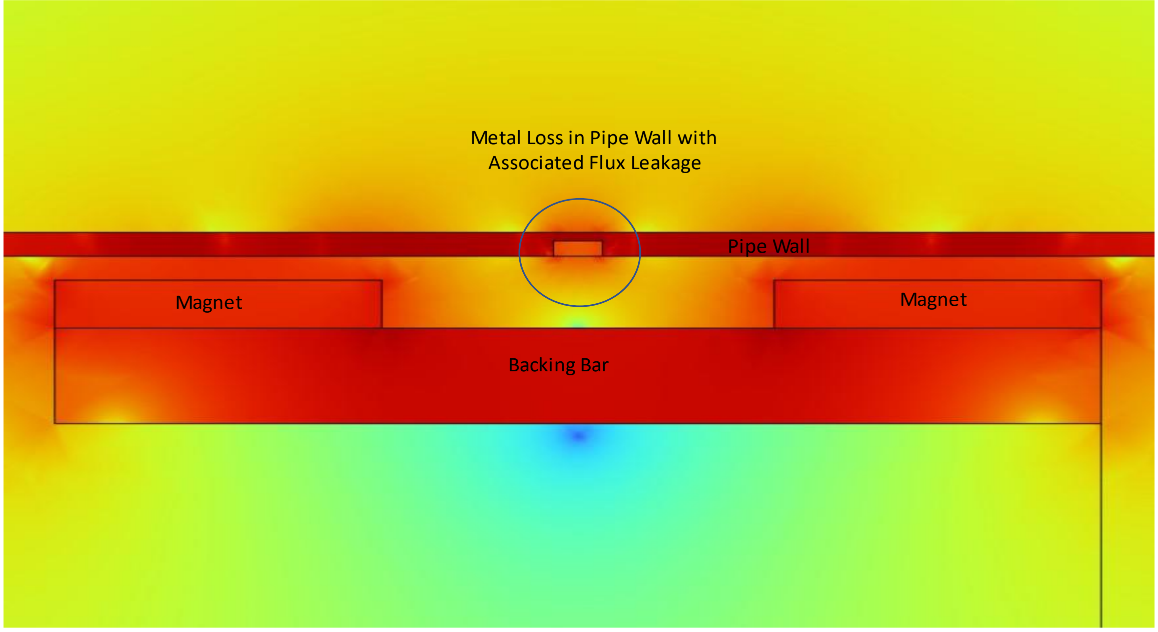

Figure 1. 2D FEA model of an MFL ILI tool and the magnetic field

When there is missing metal from the pipe wall, the magnetic field is displaced, and the magnetic field "leaks" into the area outside the pipe wall. This leakage happens because the pipe wall is saturated with the magnetic field and the magnetic field wants to follow the path of least resistance, which is now the air or material outside the pipe wall.

The MFL technique is an indirect measurement of a feature response within the pipe wall. An MFL ILI tool measures the reaction of the magnetic field to features in the pipe wall. It does not measure those features directly. The MFL technique is very good at detecting many features in a pipe wall. Figure 2 shows data collected from an MFL ILI tool. You can see two girth welds, a fitting, wall thickness change, and several metal loss defects.

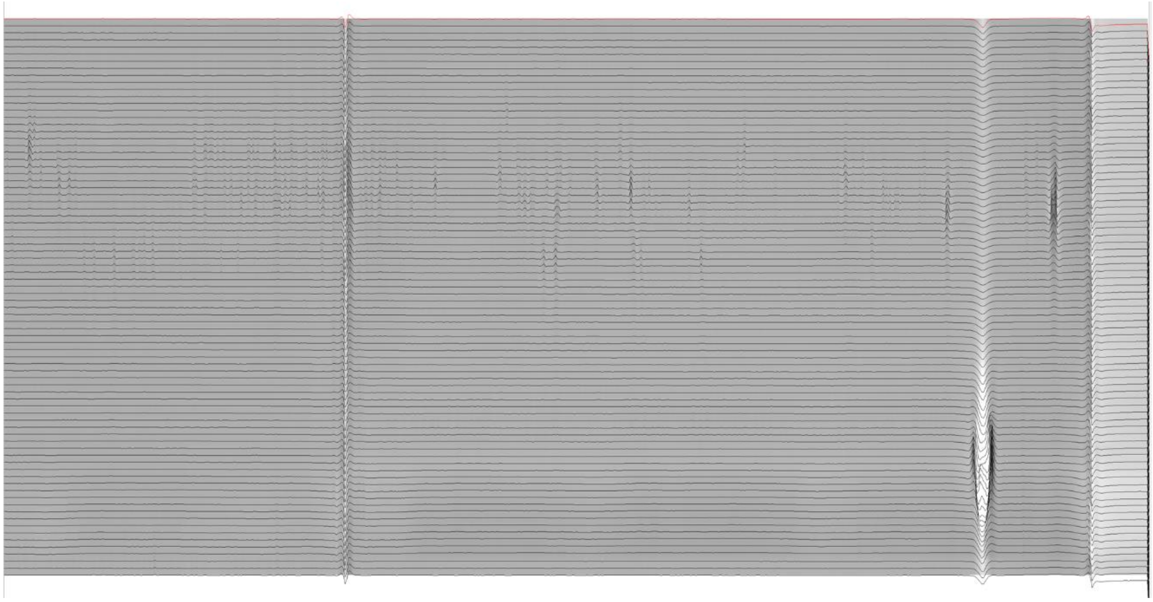

Figure 2. Example of data from an MFL ILI tool.

Quantifying physical dimensions of metal loss defects from MFL signals can be very tricky. The MFL signal is not very proportional to a metal loss defect's depth but is more proportional to the volume of metal loss that is perpendicular to the magnetic field. The shape of the MFL signal generally does not take the shape of the defect.

MFL ILI vendors develop sizing algorithms that gather characteristics of the MFL signal from the MFL ILI tool data to predict the length, width, and depth of the metal loss defect. There are many challenges that arise when developing the sizing algorithms. One approach is to figure out how changes in the MFL signal relate to metal loss defect dimensions in the same piece of pipe. This can be done by producing many metal loss defects of different dimensions, both on the interior and exterior of a joint of pipe, and then perform testing with the MFL ILI tool (e.g. pull tests). A sizing algorithm can then be developed that would be applicable to sizing metal loss defects in that piece of pipe, with that tool. Much more complexity must be considered with this basic sizing algorithm to be able to adjust for variations including:

1. Diameter of the pipe
2. Different MFL ILI tool designs within a vendor's tool fleet
3. Changing wall thicknesses
4. Pipeline materials
5. Pipeline pressure
6. Tool speeds
7. Pipeline cleanliness

There are formulas that can calculate the remaining strength of a pipeline with metal loss defects (e.g. ASME B31G). These formulas use depth and length along the axis of the pipe, as primary inputs into the equations. So, an accurate prediction of depth, length and width need to be derived from the MFL signal to perform these pressure calculations. When length, width, and depth are derived from the MFL signal there must be tolerances applied to these predictions since the MFL signal is not a direct measure of the defect.

B-H Curve

A B-H curve is used to describe the nonlinear behavior of magnetization that a ferrous (iron containing) material such as steel pipe exhibits in response to an applied magnetic field. Usually, the Y axis of a B-H curve is the B component, or the material's magnetic flux density, measured in Tesla. The X axis of a B-H curve is the H component, or the external applied magnetizing force, measured in Amperes per meter. So as steel pipe or any ferrous material is moved into proximity of a magnetic field being generated by a permanent magnet or a coil with a DC current flowing through the coil, a flux density is created inside the steel pipe wall or ferrous material. The stronger the external magnetic field, the stronger the flux density is inside the material. This is a nonlinear relationship. At first the external magnetic field creates a large change in the flux density inside the material. As the external magnetic field is increased, the additional flux density generated diminishes. Eventually, the addition of more external magnetic field has very little or no additional flux density in the material. When this happens, the material is said to reach magnetic saturation. Figure 3 shows a typical B-H curve for steel, iron, and air. It also shows that the relationship is non-linear in steel and iron.

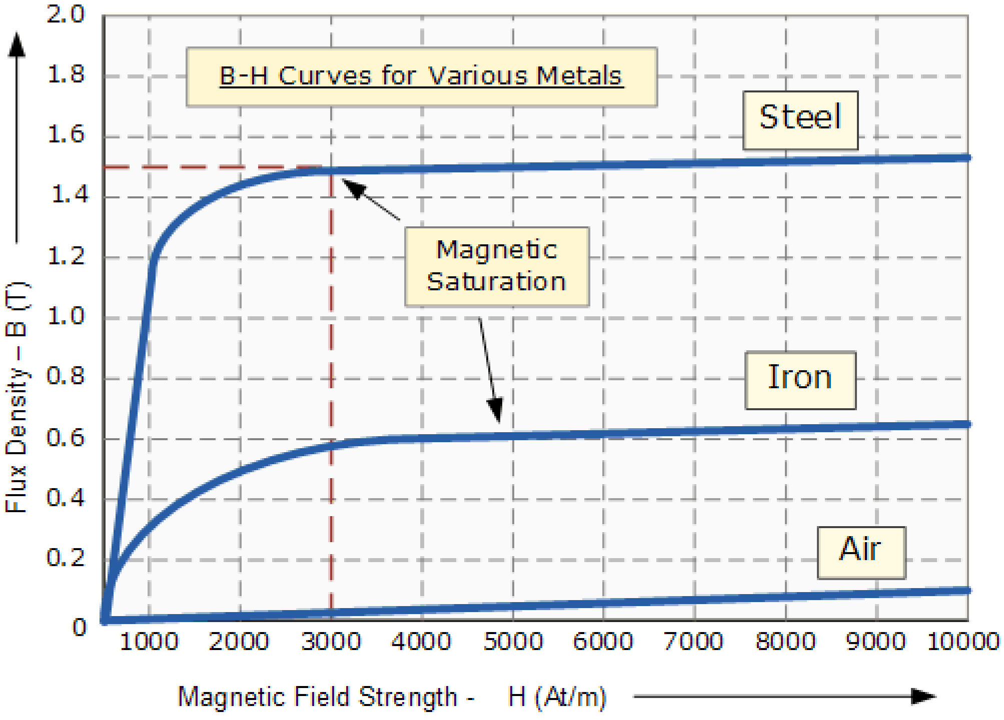

Figure 3. B-H Curves [4]

Most MFL ILI tools are designed to induce a strong magnetic field into the pipe wall. The goal of the MFL ILI tool designer is to induce a magnetic field into the pipe wall that will create enough flux density that is beyond the magnetic saturation level. This allows the MFL ILI tool to detect the smallest possible metal loss defects in the pipe wall and creates a more consistent defect response.

Flux density shifting

MFL ILI tools have a constant magnetic force applied to a pipeline. This is because the permanent magnets and magnetic circuit are fixed before the MFL ILI tool enters the pipeline. This magnetic force does not change during the inspection, unless ferrous debris in the pipeline collects on the MFL ILI tool and partially shunts (reduces) the magnetic force. The magnetic flux density (B on the B-H curve) changes as the tool travels through the pipeline and reacts to pipe thickness changes and pipeline fittings.

When the magnetic flux density increases in the pipe wall, the MFL signal surrounding a metal loss defect will increase in amplitude. When the magnetic flux density in the pipe wall decreases, the MFL signal around the same dimension metal loss defect will decrease.

So, what causes the magnetic flux density to shift as an MFL ILI tool travels through the pipeline? Let’s look at things that cause the magnetic flux density to shift, and how they can affect the detection and sizing of metal loss defects.

Pipe wall thickness

Changes in pipe wall thickness shift the magnetic flux density (B component of the B-H curve) in the pipe material. When the thickness of the pipe wall changes, it shifts the magnetic flux density up or down on the B-H curve of the pipe material, depending on if the different wall thickness is thicker or thinner. Thinner wall pipe causes the flux density to go up, and thicker wall causes the flux density to decrease. If the wall thickness increases and causes the magnetic flux density in the pipe wall to decrease down to near the knee on the B-H curve where the steel is not saturated, then the MFL detection and sizing accuracy of metal loss defects will be affected.

Using a Finite Element Analysis (FEA), a model of an MFL ILI tool was created. Several iterations of the model were run, only changing the pipe wall thickness, with everything else staying the same, to study the effect of changing the wall thickness and the level of flux density inside the pipe wall of a particular thickness. Each wall thickness from 0.625” wall down to 0.188” were plotted on a B-H curve, with the results shown in Figure 4. Note that the thicker wall pipe is down on the knee of the B-H curve. The detection and sizing of MFL metal loss defects down in this region of the B-H curve will be greatly affected, resulting in more error in the MFL metal loss defect depth sizing and decrease in detection of smaller defects by the MFL ILI tool.

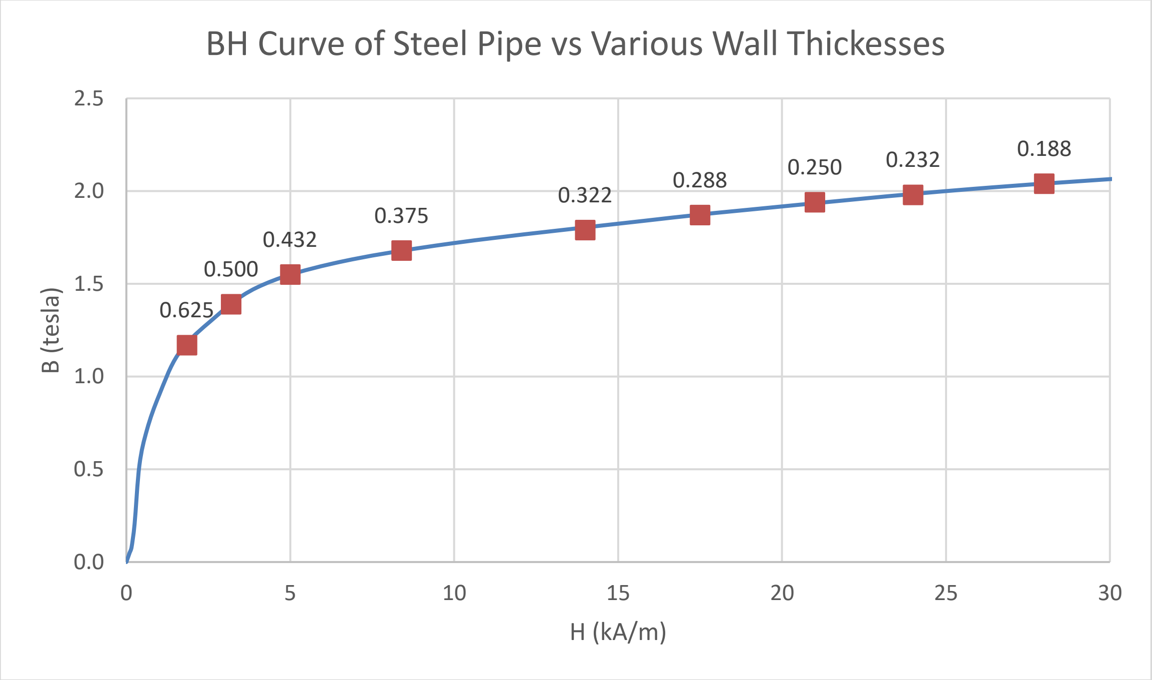

Figure 4. FEA model of different wall thicknesses(inches) along the B-H curve

Tool speed

The speed of an ILI tool traveling through a pipeline is dependent on the speed of the product going through the pipeline. Unless the ILI tool has active speed control to slow down the ILI tool, the ILI tool will react to the dynamics of fluid flow in the pipeline. In a liquid pipeline, the ILI tool speed will be constant to the flow of the liquid in the pipeline. In a gas pipeline the ILI tool speed can dramatically change due to the compressibility of gas. The differential pressure to propel an ILI tool in straight pipe can be much lower than the differential pressure required to propel an ILI tool through an elbow or pipeline fitting. In a liquid line, the fluid is virtually incompressible so the increased differential pressure necessary to push the tool through restrictions happens instantaneously. In a gas line the gas is compressible so the increased differential pressure necessary to push the tool through restrictions takes time to build behind the tool as the gas compresses. Once there is enough differential pressure, the tool is pushed through the restriction and does not require as much differential pressure to propel it through the pipeline, so the gas behind the tool will decompress and propel the tool forward. This surge of gas can propel an ILI tool to very high tool speeds until the pressure behind and ahead of the tool reach the currently required differential pressure to propel the tool. So, what effect does MFL ILI tool speed have on the B-H curve inside the pipe wall?

When an MFL ILI tool is traveling down a pipeline, eddy currents are being created near the MFL ILI tool's magnet poles as well as near metal loss defects in the pipe wall. Eddy currents are circular electric currents near the surface of the pipe wall caused by the MFL ILI tool's magnets moving over the pipe wall. Eddy currents are stronger near the internal wall of the pipe and diminish toward the external wall of the pipe. If the MFL ILI tool is not moving in the pipe there are no eddy currents present. Eddy currents are only present when a MFL ILI tool's magnets move in the pipeline. The faster the MFL ILI tool moves in the pipeline, the more eddy currents are created.

The eddy currents created over the MFL ILI tool's magnet pole pieces will cause the flux density (the B component in the B-H curve) in the pipe wall to be reduced. The faster the MFL ILI tool's speed the more the flux density will diminish [5].

The eddy currents created over metal loss defects in the pipe wall are also affected by the speed of the MFL ILI tool. These eddy currents can create several effects on MFL signals measured by an MFL ILI tool: [6][7]

1. The signal amplitude will decrease as velocity increases
2. The signal symmetry is lost
3. The signal shifts towards the trailing pole piece.
4. The signal is more affected by internal metal loss defects than external metal loss defects

The MFL ILI tool design can help overcome the effects of eddy current by lengthening the space between the magnet poles and by operating at a higher level on the B-H curve.

Stress

There has been a lot of research done on the effects of stress on MFL signals [8-13]. Steel pipe is subject to varying stress as it goes from plate to pipe and then transported, welded, and buried in the ground. There can be residual stress in the pipe due to the manufacturing process. After the pipe is buried in the ground it can be subject to bending, and line pressure when placed into operation.

Stress affects the B axis of the B-H curve of steel pipe. This effect is complicated and more prevalent around the knee of the B-H curve. Metal loss defects in pipe, especially caused by mechanical damage, can act as stress risers in the pipe wall material, lowering the B component in the B-H curve. The MFL signal amplitude can decrease with the increase of stress around a metal loss defect in pipe. This can lead to an under call of the defect depth when the defect is subject to high stress.

Most modeling of MFL metal loss defects were developed using defect sets in test pipe that were tested by pulling MFL ILI tools through pipe with winches when the pipe is not subjected to internal pressures. This method ignores the effects of stress on the modeled defect and can cause inaccuracies in the MFL ILI tool sizing algorithms when metal loss defects are subject to high stresses such as those possible when the pipe is buried and is in service.

Remanent magnetization

Once a carbon steel pipe has been exposed to the very strong magnetic field such as the passing of an MFL ILI tool, the pipe will retain some level of residual magnetization. This residual or remanent magnetization is visible on a typical hysteresis loop plot [14]. The pipe is not being influenced by an external magnetic field (H part of the B-H curve), but the pipe's residual magnetization level has some field value that is not zero (B part of the B-H curve). When a subsequent MFL ILI tool is passed through the same steel pipe, the B-H curve starts at the residual field value on the B axis of the B-H curve, and a zero value of the applied field on the H axis of the B-H curve. This creates a different B-H curve than the previous time the MFL ILI tool passed in the steel pipe. This B-H curve will be lower than the initial B-H curve. On each subsequent MFL ILI tool passage a different B-H curve will be obtained that will be lower than the previous B-H curve, but the degree of the B-H curve shift will reduce with each subsequent passage of the MFL ILI tool. Polarity of the magnet configuration of the MFL ILI tool will also affect how the BH curve responds. Figure 5 shows a hysteresis loop. Notice that at the top end of the hysteresis loop the curves converge. At high saturation levels there are less flux density (the B component in the B-H curve) effects. As you come down toward the knee of the curve there are dramatic differences of the flux density.

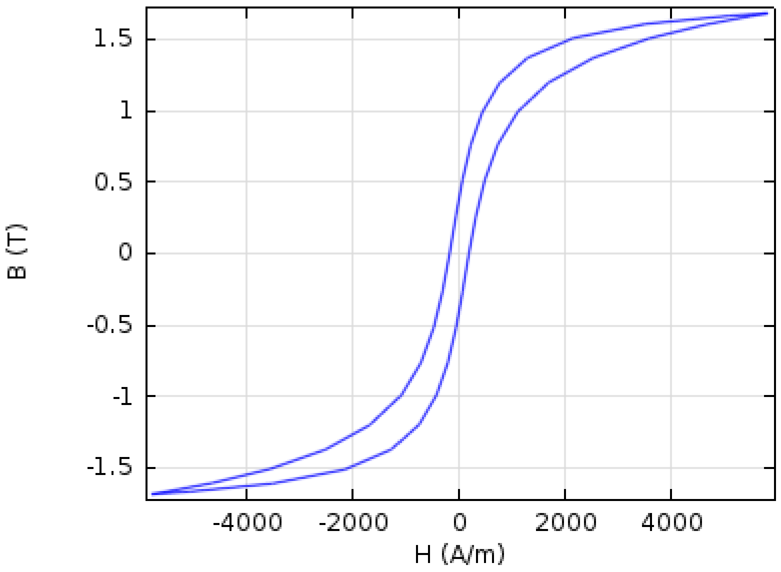

Figure 5. B-H curve showing hysteresis loop

Remanent magnetization can cause errors in MFL sizing algorithms. If the pipeline is being inspected for the first time, then the MFL signals will be strongest, and algorithms can over call the depth of the metal loss defect. If the MFL ILI tool induces a magnetic field into the pipe wall that is near the knee of the B-H curve, then there will be more variation of the B-H curve and more errors in the predicted depth of the metal loss defect.

Magnetic Properties of Pipeline Steel

Different pipeline steels have different B-H Curves. In Figure 6, it shows the B-H curve from 40 different common pipe materials [14]. Because pipe materials have different B-H curves, the resulting flux density in the pipe wall can and will be different and thus could impact the MFL sizing algorithm. The effect of the different B-H curves in different pipe materials can be minimized by inducing an external magnetic field from the MFL ILI tool that is greater than 130 Oersted (10.3 kA/m). This can normally be obtained by MFL inspection tools > 16" in thinner wall thickness. In thicker wall thickness, and in smaller diameter MFL ILI tools, the effect of the shifting B-H curve can be more dramatic and affect the MFL sizing algorithm.

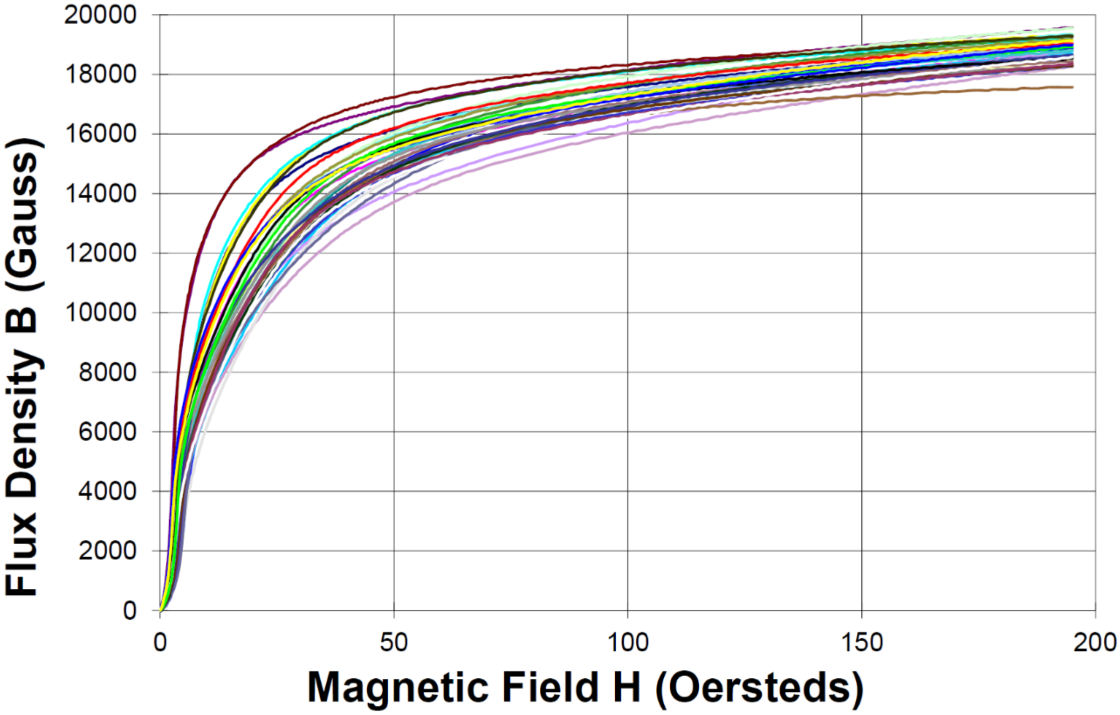

Figure 6. B-H curves of 40 pipe materials [15]

Other factors affecting MFL sizing

There are other factors other than a shifting B-H curve in the pipe wall that can affect the sizing accuracy of MFL ILI tools.

Internal vs external metal loss

MFL ILI tools will detect metal loss on both the inside and outside surface of the pipe wall. Because the main MFL sensors don't distinguish whether the metal loss is on the inside or outside of the pipe wall, MFL ILI tools have additional sensors (IDOD or proximity) that detect if metal loss is occurring on the inside surface of the pipe wall or not. The two most prevalent techniques used are low field magnetic sensors and eddy current sensors. These sensors provide a true/false detection if the metal loss is on the inside surface of the pipeline. This is important to the pipeline operator to know which surface the metal loss is occurring so that properly chosen preventative measures can be taken to minimize additional metal loss. This is also important to the MFL sizing algorithm because an identical defect on the outside of the pipe wall will have a lower signal than the same defect on the inside surface of the pipe [16].

If the IDOD sensors on an MFL ILI tool do not properly classify a metal loss defect on the proper surface of the pipe wall, then the signal will not be properly sized. If an external metal loss defect is classified as an internal metal loss defect, the metal loss defect will be undersized. If an internal metal loss defect is classified as an external metal loss defect, the metal loss defect will be oversized.

Debris in the pipeline

MFL sensors are designed to ride as close as possible to the pipe wall. When an MFL sensor travels over debris on the inside surface of the pipe wall, the distance from the sensor to the pipe wall increases (lift off or offset). This usually causes the magnetic field strength that the sensor detects to increase until the sensor is past the debris and the sensor returns to its normal distance from the pipe wall. This momentary increase in magnetic field strength can cause the same MFL signal to look similar to a metal loss defect in the pipe wall and will affect the amplitude used for sizing in a vendor's algorithm if a defect exists under the debris. An MFL data analyst must use some judgement in determining if the signal is caused by metal loss or debris or a combination.

If the MFL signal is judged to be metal loss by the MFL data analyst and the signal is caused by or affected by debris, then it would be considered a false call and the pipeline operator would not find any metal loss on the interior of the pipe wall or it would be mis-sized.

Evaluating MFL ILI tool predicted sizing vs actual results

Since the first results of data were obtained from MFL ILI tools, pipeline operators have been comparing the MFL predicted results to the actual results found when measuring metal loss. In the early days of MFL inspection, metal loss depths were not explicitly predicted, but were placed into depth ranges, based on the amplitude of the MFL signal. As technology improved and the ILI vendors started predicting the actual metal loss sizes and assigning tolerances, pipeline operators have more stringently compared the predicted to actual sizes of metal loss.

In 2005, the American Petroleum Institute (API) published API Standard 1163, “In-Line Inspection Systems Qualification” [17]. This new standard laid out new requirements for ILI tool vendors and pipeline operators. For ILI vendors, they had to create performance specifications for their ILI tools, and then perform qualification tests to show their tools meet the performance specifications. For pipeline operators, they had to verify the tool and operation parameters were met during the ILI inspection as specified and then perform validation of the sizing from the ILI tool compared to the actual metal loss defect that was found on the pipeline. The Standard then gives the pipeline operator several choices to take when the discrepancies between the predicted and actual sizing fall outside of the vendor’s ILI specification. One of these options is to have the ILI provider re-evaluate the MFL data, taking into account the information the pipeline operator has gathered to determine that the ILI tool’s performance falls outside the ILI vendors specification. It is recommended that pipeline operators provide the most accurate feedback they can on the actual size of the metal loss defects to ILI vendors. Even this simple request is problematic though and there are too many measurement variables to cover in this paper. For example, it is easier to get actual dimensions from external metal loss defects versus internal since they are visible to the naked eye and can be directly assessed. However, gone are the days when metal loss should be measured with a ruler and pit gauge. There are now laser scanning techniques that allow the full 3D measurements of external metal loss defects. Internal defects are regularly assessed with automated ultrasonic scanners. These technologies have advanced in recent years and the price of the units have decreased dramatically. Another option when tool results do not match published specifications is to have the ILI provider revise the performance specification for that specific inspection. This choice is more applicable if the MFL ILI tool is operating near the knee in the B-H curve (heavy wall, overspeed, debris, etc.) where there can be more variability in the MFL signal.

Conclusion

MFL ILI tools can sometimes struggle to meet their performance specifications. Several reasons why the MFL ILI data could be affected by the pipeline’s characteristics or operational parameters have been discussed. The flux density (B axis of the B-H curve) in pipeline steel will constantly shift as an MFL ILI tool travels down a pipeline. The B-H curve in the pipeline steel might be different than what was used to develop the MFL tool’s sizing algorithms in more controlled conditions. When the predicted vs actual sizing results fall outside of the stated tool tolerances, most ILI vendors have the capability to adjust the sizing algorithms to improve overall performance for a specific pipeline and conditions. Pipeline operators should be prepared to have a discussion with their MFL ILI vendors about when it is appropriate to adjust the MFL ILI tool’s sizing algorithm, or tool performance specification after an ILI MFL inspection to ensure the most accurate results can be achieved.

References

[1] Iowa State University Center for Nondestructive Evaluation NDE-Ed.org History of Magnetic Particle Inspection
https://www.nde-ed.org/NDETechniques/MagParticle/Introduction/history.xhtml

[2] The Australian Pipeliner The Origin of Intelligent Pigs
https://www.pipeliner.com.au/internationalnews/the-origin-of-intelligent-pigs/

[3] Bubenik, T., & Ellinger, M. & Moreno, P. "Lessons learned from ILI-to-field-data comparison" in *Proceedings, Pipeline Pigging and Integrity Management Conference*, Houston TX, 2016.

[4] https://www.electronics-tutorials.ws/electromagnetism/magnetic-hysteresis.html

[5] Usarek, Z., & Chmeilewski, M., & Piotrowski, L., "Reduction of the Velocity Impact on the Magnetic Flux Leakage Signal", *Journal of Nondestructive Evaluation* (2019) 38:28

[6] Nestleroth, J.B., & Davis, R.J., "THE EFFECTS OF MAGNETIZER VELOCITY ON MAGNETIC FLUX LEAKAGE SIGNALS", *Review of Progress in Quantitative Nondestructive Evaluation*, Vol. 12, New York, 1993.

[7] Guanyu, P., & Guo, J., & Hu, T., & Leung, H., "The Effect of Motion-Induced Eddy Current on High Speed Magnetic Flux Leakage (MFL) Inspection for Thick-Wall Steel Pipe". *Research in Nondestructive Evaluation, Vol. 31, NO 1, 48-67*, 2020.

[8] Atherton, D., & Krause, T., & Mandal, K., "Effects of Stress on Magnetic Flux Leakage and Magnetic Barkhausen Noise Signals", *Review of Progress in Quantitative Nondestructive Evaluation*, Vol. 16, New York, 1997.

[9] Makar, J., & Tanner, B., "The effect of stresses approaching and exceeding the yield point on the magnetic properties of high strength pearlitic steels", *NDT&E International* Vol. 31, 1998

[10] Liu, B., & Luo, N. & Feng, G., "Quantitative Study on MFL Signal of Pipeline Composite Defect Based on Improved Magnetic Charge Model", *Sensors* 2021, 21, 3412

[11] Gorkunov, E., & Zadvorkin, S., & Mushnikov, A., & Smirnov, S. & Yakushenko, E., "EFFECT OF MECHANICAL STRESSES ON THE MAGNETIC CHARACTERISTICS OF PIPE STEEL", Journal of Applied Mechanics and Techniqueal Physics, 2014, Vol. 55

[12] Atherton, D., & Szpunar, J., "EFFECT OF STRESS ON MAGNETIZATION AND MAGNETOSTRICTION IN PIPELINE STEEL", *IEEE TRANSACTIONS ON MAGNETICS*, VOL. MAG-22, No. 5, September 1986

[13] Mandache, C., & Clapham, L., "MAGNETIC FLUX LEAKAGE INVESTIGATION OF INTERACTING DEFECTS: COMPETITIVE EFFECTS OF STRESS CONCENTRATION AND MAGNETIC SHIELDING", *e-Journal of Nondestructive Testing* 1435-4934, 2004

[14] Nestleroth, J. B., & Davis R.J., "THE EFFECTS OF REMANENT MAGNETIZATION ON MAGNETIC FLUX LEAKAG SIGNALS", *Iowa State University Digital Repository* DOI:10.1007/978-1-4615-1987-4_58, 1995

[15] Nestleroth, J.B., & Haines, H., "NDE-4A Pipeline Discrepancy Analysis using ILI", *Pipeline Research Council International, Houston, TX*, 2013

[16] Romero Ramírez, A., & Mason, J.S.D., & Pearson, N., "Experimental study to differentiate between top and bottom defects for MFL tank floor inspections." *NDT E Int.* 42, 16–21 (2009). https://doi.org/10.1016/j.ndteint.2008.08.005

[17] "API Standard 1163 In-line Inspection Systems Qualification", *American Petroleum Institute*, Second Edition, April 2013