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Magnetic Flux Leakage Testing

Strong or Weak Magnetization?

by Vasily Sukhorukov

Magnetic flux leakage testing (MFL) technology has been used for the nondestructive testing (NDT) of various ferrous steel objects for decades. The main advantages of this method are:

- High testing efficiency of objects through air gaps or through protective coating, rust, lubricant, grease and so forth;
- Amount of testing data collected;
- Enhanced data processing;
- Enhanced interpretation by powered software;
- Minimal operator participation.

There are different MFL instruments on the market designed for various applications. Usually these instruments are intended for NDT of steel wire ropes, storage tanks and pipelines. In spite of significant design differences, depending on their function, all of these instruments comprise a magnetic system. A magnetic system creates a magnetic flux in the object under test. When there are no fractures in the object, magnetic flux leakage above the steel's surface is practically uniform. If the object contains discontinuities or its cross-section volume changes, the magnetic flux leakage distorts respectively. This distortion is detected by magnetosensitive sensors, like Hall generators or sensing coils, located in immediate proximity to the object surface. Testing data are collected, processed and displayed by an electronic unit or computer.

Strong magnetization is employed in most MFL instruments for magnetic saturation of the area under test. Powerful direct or alternating current, permanent magnets, and heavy yokes have to be used for this purpose, resulting in a large and heavy instrument design, which may be considered by users as an essential disadvantage. The question has been raised as to why the strong magnetization is necessary. Can a magnetic system be weaker, as well as smaller and lighter?

There are two sufficient reasons to uphold strong magnetization:

- Magnetic properties of the object being tested may vary because of operational conditions, mechanical and thermal effect and so on, and variation in the magnetic condition may cause reading errors. Strong magnetization makes magnetic properties uniform and so provides improved inspection reliability and measurement accuracy.
- Uniform magnetic flux within the object provides higher sensitivity to both outer and inner fractures.

Weak magnetization may not provide uniform magnetic properties, so instruments utilizing this principle may perform worse compared to those operating under strong magnetization. These weaker magnetizing instruments have lower sensitivity, especially to inner discontinuities. Readings obtained from consecutive runs vary, that is, measurement repeatability is poor. Even the use of higher sensitivity sensors and an increased gain factor may not improve inspection performance.

Besides, testing results depend on the previous magnetic condition of the object. For instance, magnetic spots arise when the MFL instrument's magnetic head is placed on (or removed from) an object, and these spots may be detected by the weak magnetization instrument and interpreted as discontinuities. Mechanical stress and, connected with this, magnetic non-uniformity also affect readings.

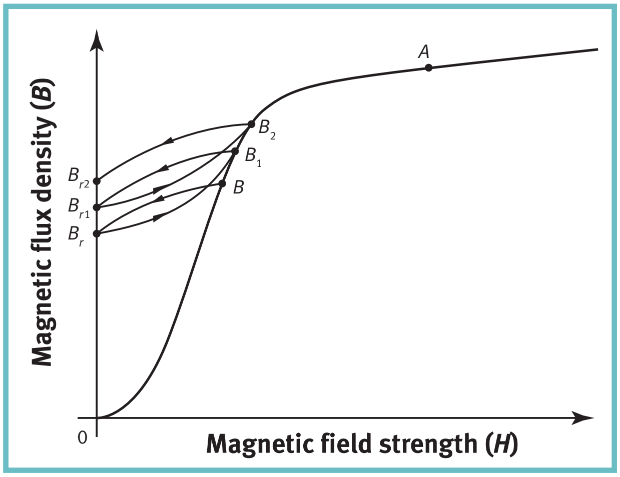

Figure 1. Magnetization of steel during inspection.

Figure 2. Inspection of a 95 mm (3.8 in.) stay bridge rope with a magnetic flux leakage testing instrument with roller system.

Steel Wire Rope Magnetic Testing

The area in which MFL technology is typically applied is steel wire rope inspection (Cook et al., 2002; Weischedel, 1985). The magnetic head of the instrument usually consists of a magnetizing system surrounding the rope under test with a permanent magnet and ferrous magnetic core, which produces the magnetic flux along the rope. While the rope passes through the head, the section of rope inside is magnetically saturated. Sensors located inside the head, close to the rope surface, catch magnetic flux leakage distortion due to broken wires (local fault) and/or loss of metallic area (LMA), which arise because of corrosion or friction.

The degree of magnetic saturation of the rope section inside the magnetic head depends on the head's magnetic system design and air gap between the poles of the magnets and the rope. Most often the rope magnetization condition is calculated to reach the working point, *A*, at the magnetization curve, $B = f(H)$, shown in Figure 1, and the magnetic flux density, *B*, volume may reach 1.9 T (19 kG). Inspection is carried out in the applied magnetic field, that is, at the magnetically saturated section of rope. The greater the rope diameter, the more powerful the magnetic system has to be; thus, the magnetic system becomes accordingly heavier and larger. Table 1 contains the weight and size of the magnetic heads for inspection of ropes with a diameter from 6 to 150 mm (0.2 to 5.9 in.).

Because of the heavy weight and strong magnetic attraction to the rope, NDT of large ropes is carried out with special roller systems designed to be installed as magnetic heads that travel along the rope, as shown in Figure 2.

A roller system may weigh approximately 100 kg (221 lb) for a 150 mm (5.9 in.) diameter rope, so the full weight of the testing instrument, including the magnetic head and roller system, may exceed 200 kg (441 lb). The diameter of the stay ropes may reach 300 mm (12 in.) or more. That is why research targeted on finding more convenient inspection technologies is important today. Some results of the research are described in an outside work (Sukhorukov et al., 2012).

TABLE 1

Weight and size of the magnetic heads for inspection of ropes with 6 to 150 mm (0.2 to 5.9 in.) diameter

Rope diameter	Weight	Size
6–24 mm (0.2–1 in.)	3 kg (7 lb)	235 × 230 × 64 mm (9.3 × 9.1 × 2.5 in.)
20–40 mm (0.8–1.6 in.)	9 kg (20 lb)	330 × 205 × 190 mm (13 × 8.1 × 7.5 in.)
40–64 mm (0.8–2.5 in.)	15 kg (33 lb)	330 × 235 × 190 mm (13 × 9.3 × 7.5 in.)
60–85 mm (2–3.3 in.)	60 kg (132 lb)	810 × 500 × 460 mm (31.9 × 19.7 × 18.1 in.)
80–120 mm (3.2–4.7 in.)	82 kg (180 lb)	895 × 520 × 440 mm (35.2 × 20.5 × 17.3 in.)
100–150 mm (3.9–5.9 in.)	112 kg (247 lb)	950 × 550 × 490 mm (37.4 × 21.7 × 19.3 in.)

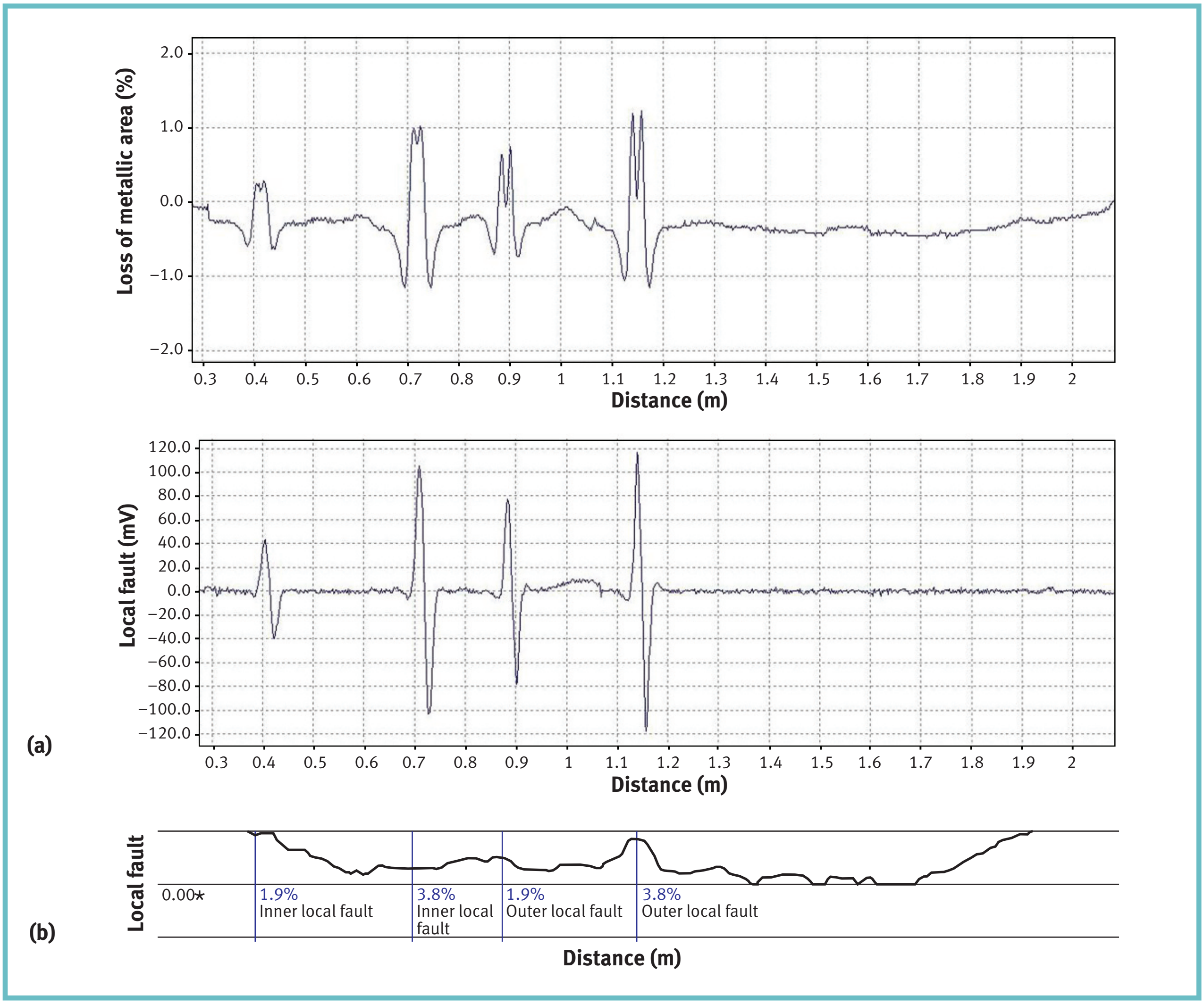

Figure 3. Results of experiment with magnetic flux leakage testing instruments: (a) strong magnetization; and (b) weak magnetization.

There is a technology utilizing weak magnetization for the inspection of wire ropes in the residual field that appeared on the market during the last few years. This technology provides rope magnetization with a device that creates a weak magnetic field; after magnetization the sensing gage assesses distortion of the residual magnetic field above the rope's surface and in this way searches for discontinuities in the rope.

According to the theory of magnetization, point B on curve $B = f(H)$ is located significantly lower than point A, as in Figure 1. Moreover, the instrument measures quite a small volume of flux leakage (B_r on the hysteresis curve) as it operates with residual magnetization.

Consecutive magnetization of rope in a weak magnetic field goes up to points B and B_r, and, as a result, causes instable readings. Because of weak magnetization, the magnetic system of the instruments is smaller and lighter compared to the strong magnetization equipment, but this is a questionable advantage, as the main features of the inspection equipment are correct measurements and reliable inspection results.

Experiment with Strong and Weak Magnetization Instruments

An experiment with rope flaw detectors using strong and weak magnetization was carried out using rod reference standards according to *ASTM E 1571-11* (ASTM, 2011). The standard 40 mm (1.6 in.) diameter, 2.1 m (6.9 ft) long rod was assembled from rods 5 mm (0.2 in.) in diameter each. Four artificial broken wires (local fault) were simulated: one inner local fault (1.9% full cross-section), two inner local fault (3.8%), one outer local fault (1.9%) and two outer local fault (3.8%), all with air gaps at 5 mm (0.2 in.), at distances of 0.4, 0.72, 0.9 and 1.15 m (1.3, 2.36, 3 and 3.78 ft) from the left end of the standard. Test results are shown in Figure 3. The inspection instrument used in an applied strong magnetic field clearly showed all discontinuities in the rod sample on both local fault and LMA traces. The instrument operating at a residual weak magnetic field only revealed the outer local fault with a 3.8% cross-section. This instrument could detect wire brakes only, being unable to measure LMA. It was also learned that the instrument operating at a weak magnetization to provide inspection in a residual magnetic field showed poor repeatability during consecutive runs because of the

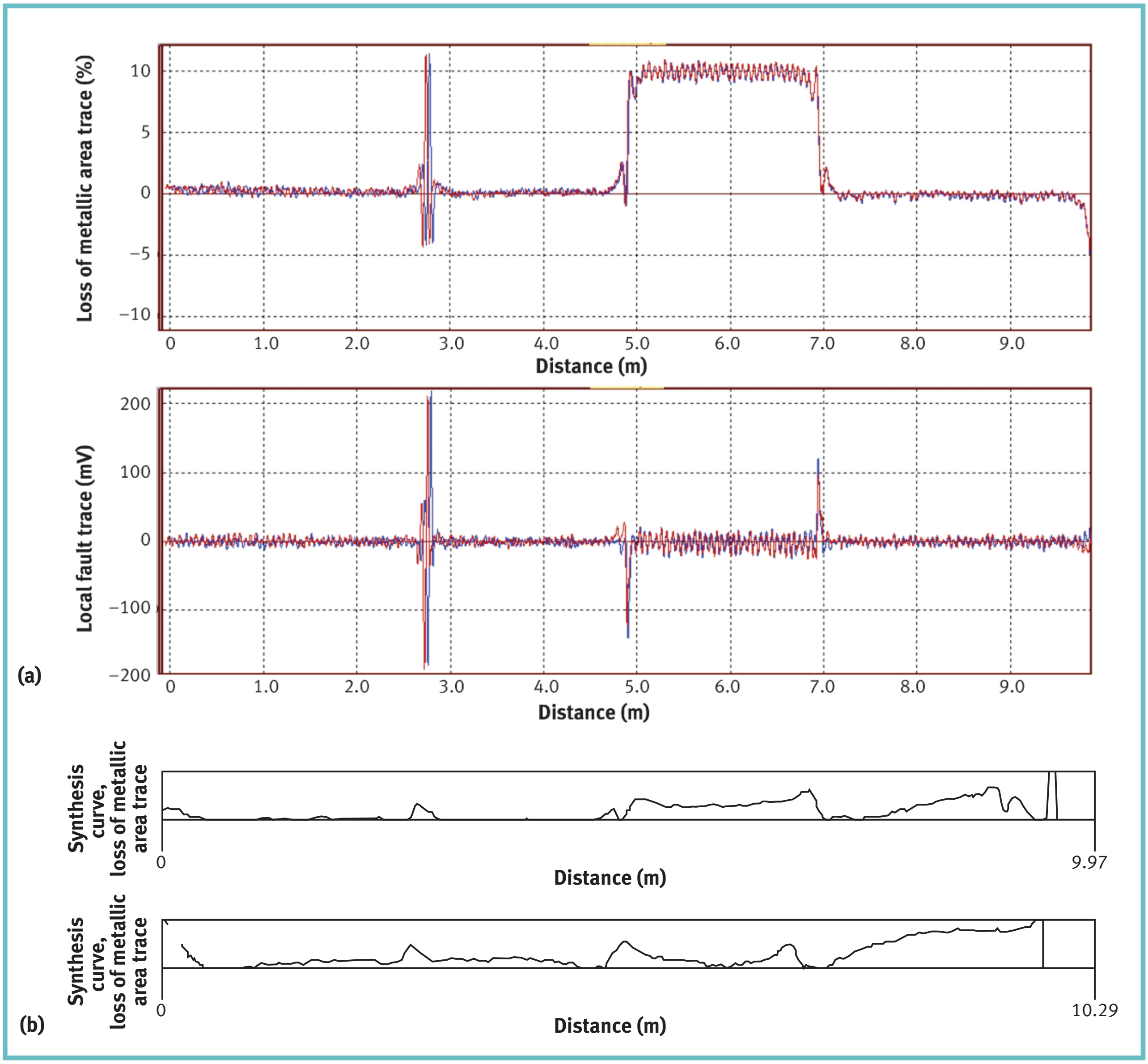

Figure 4. Test results obtained on the rope sample: (a) inspection at a strong applied magnetic field, two consecutive runs (marked as red and blue); and (b) inspection at a weak residual magnetic field, two consecutive runs.

aforementioned reason. MFL in a strong applied magnetic field provided high result repeatability.

Results obtained during two consecutive runs on the rope sample with artificial discontinuities are shown in Figure 4. The rope sample was manufactured from a rope with a 32 mm (1.3 in.) diameter, 9.9 m (32.5 ft) length and contained the following artificial discontinuities: several inner broken wires at a distance of 2.8 m (9.2 ft); and 9.8% LMA at a distance of 4.9 to 7 m (16.1 to 23 ft) from the left end. Two consecutive runs on Figure 4a, marked in red and blue, show good agreement, while runs on Figure 4b sufficiently disagree. Reading repeatability is dramatically important when consecutive runs periodically made must be compared to define any changes between them, so the rope's degradation can be evaluated and its lifetime predicted (Vorontsov et al., 2007). The same relates to rope condition monitoring based on the compared runs (Marais and Bester, 2011; Sukhorukov et al., 2003).

Other Magnetic Flux Leakage Testing Applications

In certain cases of MFL, for example, testing of flat or large diameter objects, steel magnetic saturation is difficult because of the large amount of steel adjacent to the test area and different magnetization technique utilized. Tank floors or large diameter pipelines may not be surrounded with a magnetic system, as in wire rope inspection, so a U-shaped magnetic system is therefore used for magnetization. Unlike the inspection of rope, magnetic flux density, B, created by an MFL scanner in a tank floor with a large thickness is often lower. Some of the instruments used for tank floor inspection have permanent magnets implemented into the U-shaped magnetic system; others use alternating current magnetization. MFL scanners can effectively and quickly reveal corrosive damage in a tank floor, but the depth of corrosion may be accurately measured only with an ultrasonic testing (UT) thickness gage.

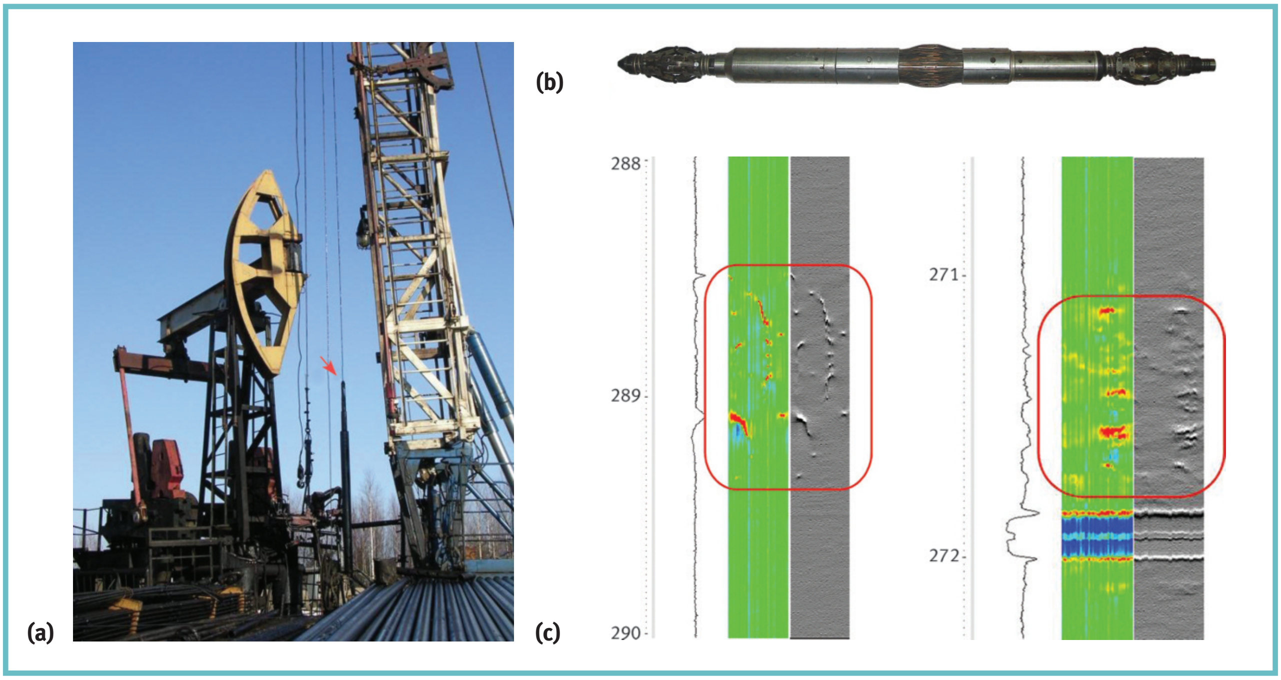

Figure 5. Nondestructive testing of an oil well pipe casing: (a) the magnetic flux leakage testing instrument (denoted by an arrow); (b) the instrument view; and (c) data records.

Pipeline inspection gages (PIGs) operate using either UT or MFL principles. MFL PIGs usually create a strong magnetic field, enabling complete saturation of the pipeline wall. A PIG travels inside the pipeline with the oil or gas flow and detects magnetic flux leakage created by fractures in the wall. A PIG usually contains main and auxiliary magnetic systems equipped with permanent magnets and sensors. The main magnetic system creates a strong magnetization with a rather large and heavy core with strong magnets, which reveals all discontinuities regardless of their location in the wall. An auxiliary magnetic system with a weak magnetization located outside of the main system provides weak magnetization to detect only those discontinuities on the inner surface of the wall. Thus, tracing and measuring the dimensions of the discontinuities become possible. An MFL PIG is heavy; for example, the gage for inspecting a 508 mm (20 in.) pipeline weighs approximately 800 kg (1764 lb).

Figure 5 shows another MFL device with magnetic saturation: the instrument for pipe casing NDT of an oilfield borehole. Its magnetic system is similar to that of a PIG but uses a direct current for magnetization. A cable hoist is used to move the device through the pipe to reliably detect fractures and corroded areas on both the inside and outside surfaces.

Conclusion

MFL instruments that provide inspection using applied strong magnetic fields and magnetically saturate testing areas show good repeatability, as well as high sensitivity to outer and inner fractures. They may also accurately measure loss in the amount of steel due to corrosion and friction. However, to create a strong magnetic field, such MFL instruments require a sufficient weight and size.

When saturation conditions are unobtainable, relatively weak magnetization may be used for inspection, but readings are less repeatable and accurate.

Up-to-date weak magnetization products, especially operating in a residual magnetic field, seem attractive because of their relatively low weight and small size, but their performance is quite poor and such products are inferior to strong magnetization instruments in this respect. This is very important for objects under test monitoring and to assess their lifetime prediction.

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