Hindawi Publishing Corporation
Advances in Materials Science and Engineering
Volume 2013, Article ID 708396, 8 pages
http://dx.doi.org/10.1155/2013/708396

Research Article

Investigation of B_x and B_y Components of the Magnetic Flux Leakage in Ferromagnetic Laminated Sample

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Received 4 May 2013; Accepted 10 September 2013

Academic Editor: You Song

The magnetic flux leakage (MFL) technique is most commonly used for crack detection from iron bars, laminated sheets, and steel tubes of ferromagnetic nature. Magnetic flux leakage system induces a magnetic field and detects magnetic flux lines that "leak" or change because of a discontinuity in the magnetized area. An inductive coil sensor or a Hall effect sensor detects the leakage. Magnetic methods of nondestructive testing (NDT) depend on detecting this magnetic flux leakage field. The ferromagnetic specimen is magnetized by suitable methods, and flaws which break the surface or just the subsurface distort the magnetic field, causing local flux leakage fields. It is very important for industrial applications to detect cracks and flaws in metal parts of the steel bridges, power stations, military tools and structures, and so forth. In this study, the inspection of cracks in laminated sheets under longitudinal magnetization will be discussed in detail.

1. Introduction

There are varieties of nondestructive techniques for industrial use. Most of them are suitable to find out of the surface cracks on the laminated samples, pipe line tubes, and liquid storage tanks. The basic factors that affect the method of nondestructive inspection chosen are product diameter, length, and wall thickness, fabrication methods, type and location of potential discontinuities, specification requirements, and extraneous variables such as a scratch, which might cause a rejectable indication, even though the product is acceptable.

The most widely used nondestructive testing techniques for weld inspection of tubular products are ultrasonic, eddy current, magnetic flux leakage, radiographic, liquid penetrant, and magnetic particle. The first four are reliable for identifying internal flaws, whereas the last two are most reliable for detecting surface flaws. Each of these techniques has specific advantages and limitations [1].

The related component is magnetized to a level at which the presence of a significant local reduction in material thickness causes sufficient distortion of the internal magnetic field to allow flux lines to break the test surface at the site of the discontinuity. The applications of magnetic flux leakage (MFL) method and suitable sensors are used to give an electrical signal at the leakage site. This signal may operate an audible or visual alarm to alert the inspector, or may store the event for computer mapping of the area. MFL technique requires two basic things, a method of magnetization and a method of detecting the leakage field.

The magnetization can be achieved by using electromagnets or permanent magnets. There are several types of sensor that can be used in MFL. These types include search coils, Hall effect sensors, magnetostrictive devices, and giant magneto impedance (GMI) sensors [2]. The permanent magnets and Hall Effect sensors are the most commonly used for MFL technology.

Search coil sensors give a voltage signal proportional to the flux density of the field passing through the sensing element. Figures 1 and 2 show the field patterns for pitted material. The position of the sensing elements is parallel to the scanning surface; it follows that it is the normal (vertical) component of the magnetic flux leakage vector which will be measured. If the sensing elements were to be arranged perpendicular to the surface, then it would be the tangential (horizontal) vector that would be measured.

Because the magnetic flux leakage method responds to both far side and near side corrosion and cracks, it is necessary to introduce a strong magnetic field into the component

Figure 1: Cross-sectional area of the sample with full of line of fluxes.

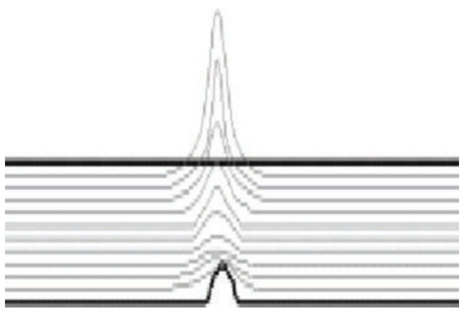

Figure 2: Cross-sectional area of the sample with full of line of fluxes and company of corrosion pit.

wall. The closer this field becomes to saturation for the component, the more sensitive and repeatable the method becomes [3–5].

In the MFL technique, permanent magnet or electromagnet systems is used to magnetize a sample to saturation. Regions of reduced thickness, such as a corrosion defect or surface cracks, force magnetic flux leak into air [6]. This flux leakage is detected using number of turn search coil or a Hall effect sensor and is correlated with the size and location of the defect [7]. The wall thickness that can be tested is limited by the ability of the magnetic flux to penetrate the wall and the ability of the sensor to detect flaws at a distance from the wall [8].

However, nondestructive testing technology has gained significant importance in modern industrial processes for reducing down time and enhancing safety and productivity [9, 10]. Great success has been achieved in the pipeline industry using the magnetic flux leakage technique to locate and size defects in oil and gas pipelines and laminated sheets in steel bridges, power stations, and steel wire robe inspections [11, 12].

It is very important to understand the physics of magnetic flux leakage method (MFL) due to the implemention of the sensing process of cracked region. The understanding of mechanism of flux leakage in a laminated sheet, pipe lines, and other applications gives more accurate analyzing capability during the experimental study. This study investigates the inspection of cracks in laminated sheets under longitudinal magnetization.

2. Experimental Setup

The magnetic flux leakage measurement system consists of two main processes such as magnetization and magnetic measurement systems. In this study, the sample was magnetized along the sample length on the longitudinal direction. Magnetization system was constructed with two serially connected magnetization coils. A soft iron core was located into the magnetization coils such as a flux concentrator.

The system was energized by 5 V and 500 Hz sinusoidal signal. The signal was obtained from a HP 33120 A arbitrary waveform generator then was amplified by a SONY ES505 power amplifier. An isolation transformer was used to filter DC signal which occurs during the amplification of power amplifier as given in Figure 3.

It is important to understand the energizing mechanism of the magnetization progress. The energizing progress consists of two basic stages. The first stage produces magnetic field strength when the magnetization current is applied to the magnetization coils. These coils have about 250 turn windings with 1.2 mm wire thickness. The second stage energizes the sample along the longitudinal direction.

When the magnetization current was applied to the magnetization coils at 500 Hz and 1 A, a magnetic field strength occurs in the serially connected magnetization coils. This causes a magnetic flux distribution into the soft iron (SiFe) laminated core. When the system is energized, the occurred magnetic flux passes through into the sample. Natural path of the magnetic flux lines is along the length of the longitudinal direction of the sample. If there is no discontinuity in the laminated ferromagnetic material, the produced magnetic flux flows into the sample due to its high magnetic permeability.

If there are any cracks, holes, and discontinuities in the laminated sample, the magnetic flux leakage occurs [3]. This magnetic flux leakage is perpendicular to the sample surface. To capture surface flux leakage, a 250-turn air-cored search coil was used. The search coil was moved on the sample along the longitudinal direction by a driven stepper motor system as shown in Figure 4.

A 250-turn air-cored search coil was used to capture surface magnetic flux leakage signal which occurs around cracks and discontinuities in the sample. The captured signal was a sinusoidal in nature, so a (dB/dt) signal was induced on the search coil (see (1))

$$B_x = \frac{V_{av}}{4.4 N_2 f A} \text{ (Tesla)}, \quad (1)$$

$$V_{av} = 4.4 N_2 f A B_x \text{ (Volt)}, \quad (2)$$

where B_x is magnetic flux density in (Tesla), V_{av} is the average value of induced signal on the multi turn search coil, $N_2 = 250$ is the number of search coil, $f = 500$ Hz is magnetization frequency, and A is the cross-sectional area of sample. 500 Hz was found to be the most suitable operating frequency for this investigation and it was kept constant for all measurements.

Magnetic field strength was measured by an rms sensing voltmeter HP 34401 A during the experimental study for the control purpose. Magnetic field strength H was measured to

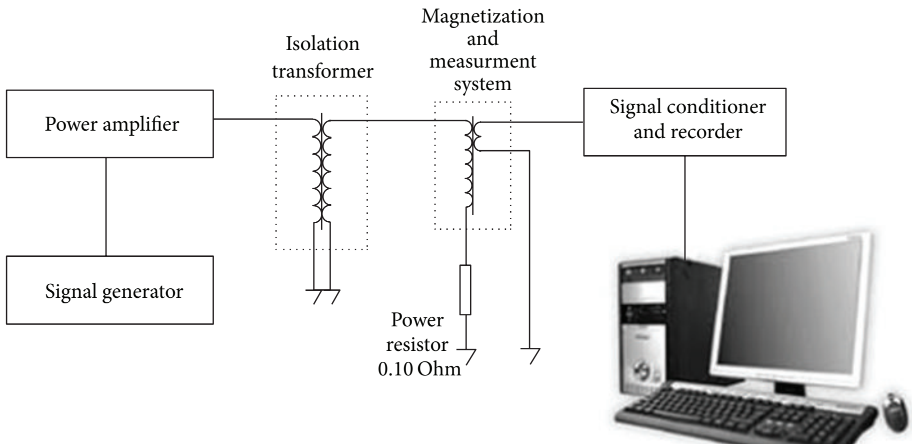

Figure 3: Block diagram of the magnetization system.

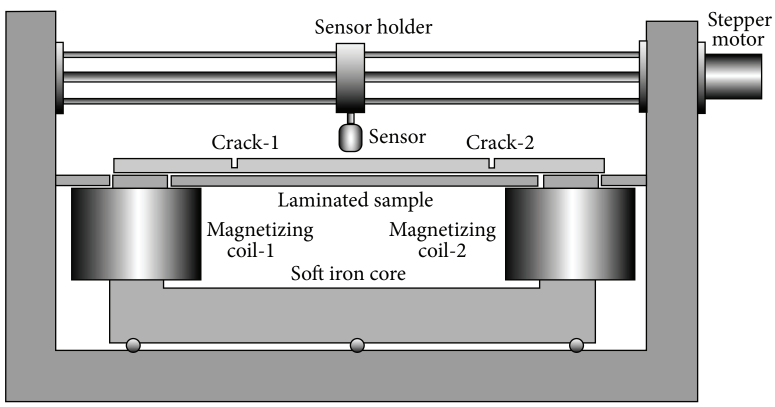

Figure 4: Schematic diagram of the magnetic flux leakage measurement setup.

control experimental conditions during the study. Magnetic field strength H was calculated with the following formula:

$$H = \frac{\sqrt{2} N_1 V_{\text{rms}}}{\ell R} \text{ (A/m)}, \quad (3)$$

where H is magnetic field strength in (A/m), V_{rms} is rms value of the induced signal, $N_2 = 250$ turn is the number of the magnetization coils, ℓ is the total length of the magnetization core, and $R = 0.1\ \Omega$ is the resistivity of power resistor, which is serially connected between magnetization coil and ground state.

The sensor signal was conditioned by using an electronic interface. It was amplified and filtered then passed through the HP 34970 A digital signal processing switch to capture the sensor signal for every second. The data was collected automatically by using a computerized data accusation system.

The behaviors of the B_x and B_y components of the magnetic flux leakage are very important during the discontinuity search in the laminated sample. The total flux density comes up from the magnetization coils which are serially connected to each other as given in Figure 4. The surface flux leakage jumps from core legs to the laminated sample and follows the path along to sample length during to longitudinal direction. During this stage, B_x and B_y components occur due to discontinuity into the laminated sample. The reason of discontinuities could be surface and subsurface cracks, corrosion pits, local stress, and so forth.

B_x and B_y components of the flux leakage were captured by single and number of turn search coils during the measurements. The data was collected by using an HP 34970 A data acquisition switch unit instantaneously. The collected data were recorded by a computer to use them for the signal processing.

Three basic experiments were performed during the study. In the first stage, a U-type magnetization core was energized without sample to find out behavior of the magnetic flux leakage. This was an opportunity to observe flux distribution on just about core legs and between the legs in the space.

In the second stage, a sample was located on the U-core legs without any cracks and discontinuity. The sample was touched on the cross-sectional surface of the core legs at the both ends of the laminated sample. The magnetic flux was transferred from core legs to the sample just on the cross-sectional surface of the legs. The magnetic flux travels from one end to other if there are no cracks.

In third stage, the particularly cracked sample was located on the core legs with two cracks to capture cracked regions as a function of the distance and surface magnetic flux leakage.

Finally, the three stages of the study are compared to find out cracked regions with high sensitivity, repeatability, and less error.

3. Results and Discussion

3.1. Measurement of the Magnetic Flux Leakage (MFL) between Core Legs without Sample. A U-type magnetization core was used to produce magnetic flux density to detect discontinuities and cracks in the laminated sample as given in Figure 4. In the first stage of the study, the core is energized by a serially connected two magnetization coils without test sample.

The U-core was acting as a flux concentrator. The flux which is produced by magnetization coils is collected and transferred to the air by a soft iron U-type magnetization core. Produced magnetic flux density has three components, as B_x, B_y, and B_z. Magnetic flux density is given as in (4)

$$\vec{B} = \vec{B}_x + \vec{B}_y + \vec{B}_z,$$
$$B = \sqrt{B_x^2 + B_y^2 + B_z^2}. \tag{4}$$

In this study, B_x and B_y components of the flux density are most important to explain the position of the cracked region. Because of this, the B_z component of the magnetic flux density was ignored during the study. The produced magnetic flux density transferred on to the air just from the cross-sectional surface of the core legs. B_y is the major component of the flux density on the core legs as given in Figure 5. This is an expected result due to the position of the core legs. Longitudinal axis of the legs is located on y-direction.

The search coil sensor measured about 3.5 V just on the core leg as a B_y component. B_x component of the MFL signal also measured about zero volt just on the cross-sectional area of the core legs as given in Figure 6. It was shown that the B_y component of magnetic flux was in opposite nature with B_x component of the MFL signal.

Total flux density was constant for specific frequency and magnetization currents according to (4). Because of this, when B_x component of flux density increases, the B_y component of the flux density decreases due to constant flux density of magnetic system. When scanning by search coil from left corner of U-core to right corner was carried, it was found that B_y component becomes stable at about 1.2 V between 5 cm to 20 cm distance on U-type core.

B_y component of the flux density converts to B_x component due to jumping of the flux lines from core legs to air. Although this B_x component of the flux lines increase apparently from ground state to about 1.6 V sensor response due to the decreasing percentage of B_y component of flux lines. Both components of flux density behave symmetrically just on the middle of the U-core.

The B_y component of flux lines increased to maximum value of 3.5 V. It decreased to minimum value of 1.2 V sensor response at about 3 cm away from the left corner of U-core. The variation of the sensor response was uniform up to right part of the U-core as given in Figure 5. If scanning was carried on by a search coil sensor, it was stable up to 18 cm away from the left corner. After this point, sensor response suddenly increased from 1 V to up to 3.5 V. An expected sensor response was achieved along the length of the U-core. B_y component of the flux density is higher at just over the core legs and B_x component of the flux density was getting lower about the ground state just on the core legs. When the sensor leaves from the core legs, suddenly B_x component increases up to maximum value and B_y component of the flux density

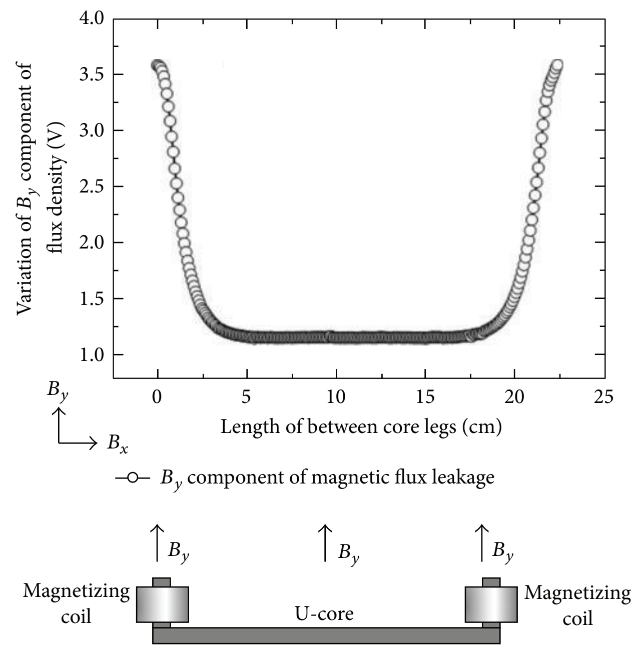

FIGURE 5: Variation of the B_y component of the magnetic flux leakage without sample between core legs.

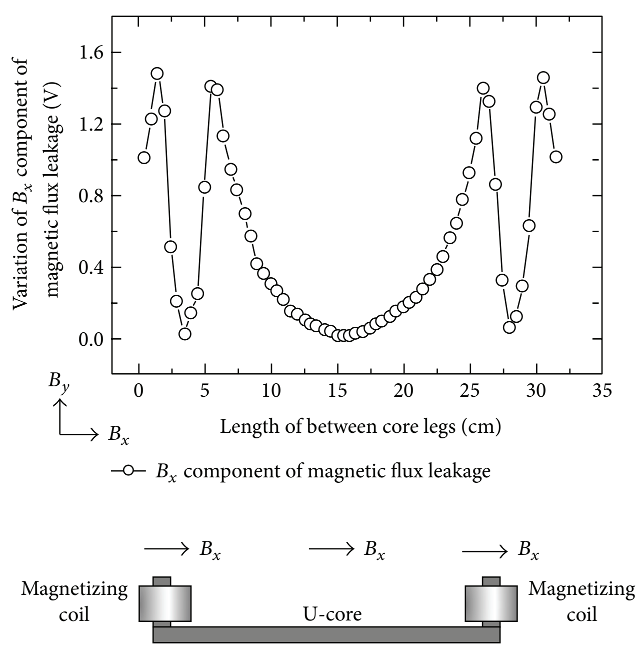

FIGURE 6: Variation of the B_x component of the magnetic flux leakage without sample between core legs.

decreases lower level during the scanning process as shown in Figure 6.

3.2. Measuring of the Magnetic Flux Leakage (MFL) on Full Length Laminated SiFe Sample without Cracks. In the second stage of the study, a full length laminated SiFe soft ferromagnetic sample was located onto the U-core legs without any cracks and discontinuities. The purpose of this is to find out how does flux flow inside the full length laminated sample without any crack and discontinuities from one leg to the other. Variation of B_x and B_y components of flux density could be achieved when a sensor scans on two dimensions along the length of the sample between core legs as a function of displacement.

All flux lines on y-direction on the core legs due to this B_y component of magnetic flux density are higher than the B_x component of magnetic flux on the core legs. Magnetized core transferred (MFL) magnetic flux lines from core legs to the laminated sample. When the flux lines meet the laminated sample, they suddenly jump on and B_y component of magnetic flux lines decreases exponentially to the minimum value as shown in Figure 7. B_x component of magnetic flux lines also gradually increases up to maximum value in linear region as given in Figure 8 at about 4 cm away from the origin. The reason for this is that B_y component of magnetic flux lines rotates on the sample due to its high magnetic permeability.

Most of the B_x components of magnetic flux lines are used to magnetize sample along the x-direction. Unfortunately, the sample is not saturated, and because of this, so many domain walls occur in the sample. This behavior causes B_y component of magnetic flux lines in the length of the laminated sample. Because of this, the amplitude of B_y component of magnetic flux lines was measured as 1.8 V even if $B_x = 0$. B_x component of the magnetic flux lines is in charge of the magnetization of the laminated sample. Because of this, some of the B_x component of the magnetic flux lines disappears to magnetize the sample. According to magnetic domain theory, all spins become parallel to the x-direction when the magnetic flux lines pass along the length of the sample [13].

It is not easy to keep all the spins parallel to the sample length. The system should spend some energy to keep them parallel. Keeping the spins parallel of each other causes a power loss in the sample. Due to this, some of the magnetic energy converts to heat to compensate for power loss.

B_y component of MFL gets higher on the core legs due to the increasing flux density just on the core legs. The magnetic flux lines were bending over the sample and B_y component of flux lines gets lower. On the other hand, the B_x component of the magnetic flux lines gets higher just about the core legs. Then, they drop to zero in the middle of the full length of the sample. The reason for this is the magnetization of the sample. Because of the magnetization of sample, power loss occurs in the laminated sample.

3.3. Measuring of the Magnetic Flux Leakage (MFL) on Laminated SiFe Sample with Two Cracks. A SiFe laminated sample was located on the legs of U-core with two cracks. Two cracks were particularly prepared on the laminated sample to investigate the variation of the magnetic flux leakage just about cracked regions. B_x and B_y components of surface magnetic flux leakage were measured by a search coil. The sensor scanned from left corner to the right corner of the U-core by a stepper motor system. Obtained B_x and B_y components were similar as discussed above.

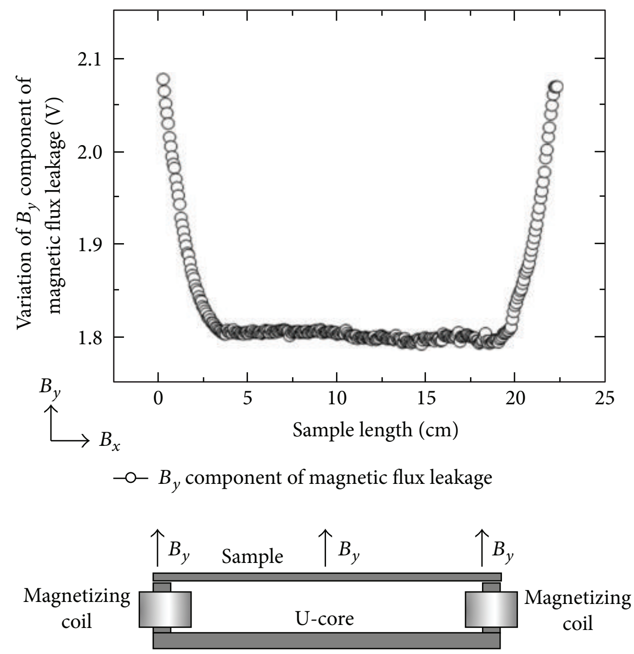

FIGURE 7: Measurement of B_y component of the magnetic flux leakage with sample between core legs without cracks.

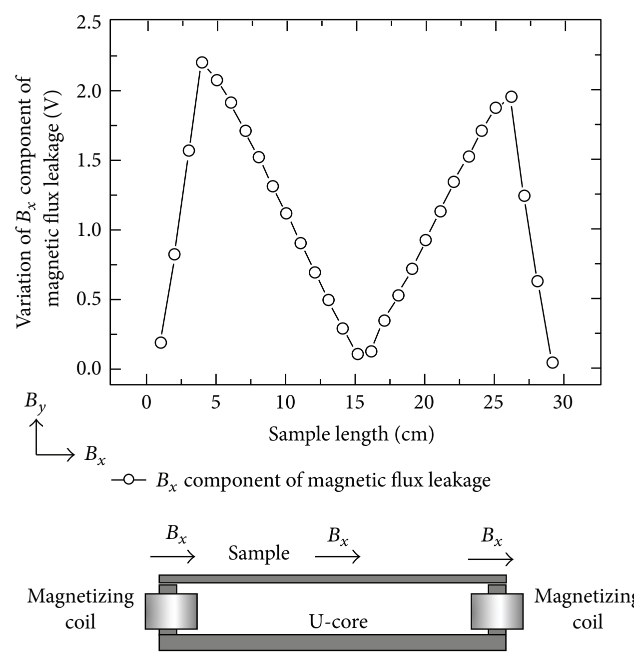

FIGURE 8: Measurement of B_x component of the magnetic flux leakage with sample between core legs without cracks.

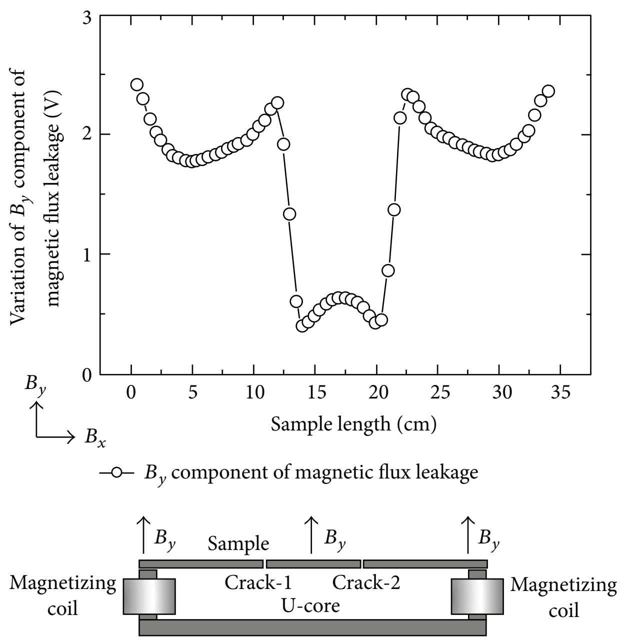

FIGURE 9: Measurement of B_y component of the magnetic flux leakage with sample between core legs with two cracks.

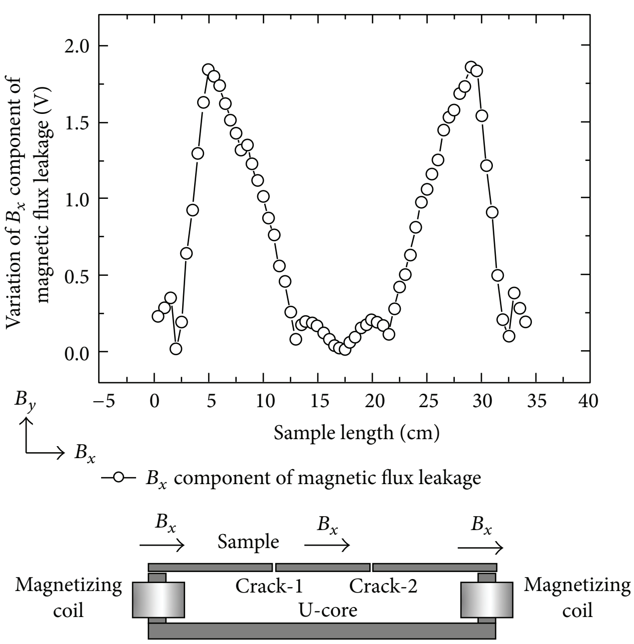

FIGURE 10: Measurement of B_x component of the magnetic flux leakage with sample between core legs with two cracks.

The B_y component is higher at about core legs then gets lower between core legs at the first crack as shown in Figure 9. When the sensor approaches to first crack, sensor response increases almost same as the value at about on the core leg. If the sensor passes through the crack, the sensor response gradually decreases up to the minimum value. B_x component of the magnetized sample was captured by a single turn search coils as shown in Figure 10. Search coils were located 5 mm away each other onto the laminated sample. A magnetic flux flows into the search coils when the sample is magnetized by a sinusoidal current at 500 Hz up to 1 A. According to Biot-Savart law and Faraday's law, a current is induced into the single turn search coils as (dB/dt).

A flux concentration occurred in the legs of the C-core during the energizing of magnetization coils. The generated flux jumped on the laminated sample from the legs of the C-core. B_x and B_y components of the magnetization were measured during the experimental study individually. A variation of the surface magnetic flux leakage was obtained around the cracked region. The amplitude of the B_x component of surface flux leakage was increased up to 2.0 V just after the core legs. Measured signal is gradually reduced down about zero Gauss on the cracked region. When the sensor moved on from left to the right, B_x component slightly increased to 0.25 V then decreased to zero. Signal amplitude reached up to 0.25 V again than decreased to zero on the cracked region. This variation was an evidence of the crack in the laminated sample.

Variation of the sensor signal is most important on y direction. Therefore, measurement of the B_y component is most suitable then the B_x component of the surface flux during the crack detection experiment. The large amount of variation occurs on the B_y component. This variation supplies more accuracy and information about cracked shape, depth, and width. This gives an opportunity to define the cracks or flaws in the material.

Sensitivity and repeatability are the most important issues for nondestructive testing. The estimation of crack width, depth and shape are also important to improve the accuracy. If the sensor moves from left to right, a signal variation occurs.

When the sensor locates just over the cross-sectional area of the core legs, more signals induce on the search coil due to the high concentration of the B_y components of magnetic flux density. Amplitude of the induced signal is reduced from 2.5 V to 1.75 V due to changing the position of the sensor on the sample as given in Figure 9. Most of the flux lines are bending over the sample and prefer to go in the laminated sheet. Therefore, most of the B_y components of the flux lines converted to B_x components. This converting causes a decrease in the amount of the B_y components of flux lines. The induced sensor signal also decreases at this region due to the same reason. When the sensor approaches to a crack, surface flux leakage lines suddenly prefer to go in air.

Therefore, the amount of the B_y components of flux lines increases to certain levels which gives an evidence of discontinuities. Then, the sensor signal suddenly drops to the minimum value when the sensor arrives to the other side of the cracked region. The amplitude of B_y component of the surface flux dramatically changes because of the discontinuity of crystal structure. When a crack occurs, the permeability of the related region is replaced with air. The magnetic flux lines escape to space from the laminated sample. This causes a dramatic change in the sensor signal. This behavior is very important to find out cracks and flaws in the laminated sheets.

A tremendous signal drops occur just on the cracked regions. The occurred discontinuity affects the flux distribution along the length of the magnetization of sample. The

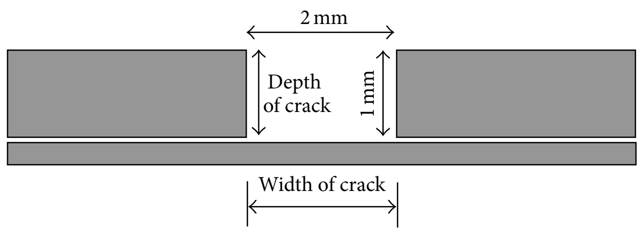

Figure 11: The shape of crack.

magnetic domains become parallel to each other when the laminated sample was magnetized.

Theoretically, a single domain occurs if the sample approaches to saturation on the sample surface. Occurred discontinuity causes a distortion of the cracked region on the magnetic domain structure. The surface magnetic flux prefers to jump to the other side of the cracked region. Due to this, a signal drop occurs just on the cracked region. If the sensor captures the signal variation during the surface scan this shows that there is discontinuity.

It is possible to find out surface cracks using surface magnetic flux leakage method as given above. There should be some more study to find out crack width, depth, and shape for unknown cracks. Figure 11 belongs to regular crack shape.

We need to prepare a data bank to compare the signals with unknown cracks. It is also an important issue to do signal processing on the captured signal to remove noise from the sensor output and to get a clear signal. The signal processing improves signal quality and decreases the measurement errors. This is important to obtain accurate experimental results. When all this issues come together, we can have a tool to obtain cracks on the machine parts, power stations, steel bridges, railways, and so many industrial applications.

4. Conclusions

In this study, the mechanism of the surface magnetic flux leakage technique was investigated to obtain a tool for non-destructive methods. Magnetization process was analyzed in detail in three stages.

(i) In the first stage, a U-type magnetization core was energized without sample to find out the behavior of the magnetic flux leakage. The B_y component of the magnetic flux is getting higher on the core legs, but B_x component of the magnetic flux leakage reaches nearly the ground state on the core legs. The B_x component of the magnetic flux leakage is reaching the maximum value due to conversion of the B_y component to the B_x. Therefore, both components approached to minimum value between the core legs.

(ii) In the second stage, the sample was located on the U-core legs without any cracks and discontinuity. The located sample behaved as bridge between core legs and transferred magnetic flux from one core leg to the other. The B_y component of the magnetic flux leakage is higher, but B_x component of the magnetic flux leakage reaches the minimum on the core legs. B_y components almost converted to B_x on the sample and due to this, B_y suddenly approached to minimum value. B_x increased to reach the maximum value then approached to minimum value on the middle of the sample between core legs because of the power loss.

(iii) In the third stage, the particularly cracked sample was located on the core legs with two cracks to capture cracked regions as a function of the distance and surface magnetic flux leakage. Sudden change of the B_y component on the cracks has given an opportunity to capture cracked regions on the ferromagnetic laminated sample. The variation of the B_x component is not useful for crack detection due to the complexity of capturing B_x component. However, capturing the B_y component is very easy. It is possible to collect data only scanning the surface by a search coil which is perpendicular to the sample surface.

(iv) The magnetic flux was separated in two parts B_x and B_y components into the ferromagnetic laminated sample. B_x component was parallel to the length of the sample and B_y was also perpendicular to the sample surface. It is concluded that the measurement of the B_y was important to find out surface cracks by using magnetic flux leakage method.

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