CHAPTER 5
MAGNETIC PARTICLE TESTING

I. HISTORY AND DEVELOPMENT

Magnetism Discovered

The ancient Greeks, originally those near the city of Magnesia, and also the early Chinese knew about strange and rare stones (possibly chunks of iron ore struck by lightning) with the power to attract iron. A steel needle stroked with such a "lodestone" became "magnetic" and around the year 1000 AD, the Chinese found that such a needle, when freely suspended, pointed north–south.

Early Physicists Develop the "Basics" of Magnetism

In the late 1700s and the early 1800s, several exiting new discoveries were made in the field of Physics that paved the way for today's magnetic particle testing (MT) technology.

In the 1700s, Charles Coulomb, a French physicist, discovered that "the magnetic forces of attraction and repulsion are directly proportional to the strength of the poles and inversely proportional to the square of the distance from them," (the inverse square law). He also invented the magnetoscope and magnetometer, which are devices for measuring the Earth's magnetic field strength.

Until 1821, only one kind of magnetism was known; the one produced by iron magnets. Then, Danish scientist Hans Christian Oersted, while demonstrating to friends the flow of an electric current in a wire, noticed that the current caused a nearby compass needle to move. Physicist Andre-Marie Ampere, who concluded that the nature of magnetism was quite different from what everyone had believed, studied this new phenomenon in France. It was basically a *force between electric currents:* two parallel currents in the same direction *attract*, in the opposite direction they *repel*. This proved that magnetic fields exert an influence on current flow.

Phenomenon Discovered Leading to Inspection Principles

In the late 1800s it was observed that a compass needle deflected when it passed over a crack in a magnetized cannon barrel. In the 1920s it was discovered that iron filings on parts held in a magnetic machining chuck produced patterns showing the magnetic lines of flux. Closer investigation revealed patterns that corresponded to discontinuities within the parts.

This is probably the earliest documented application of the magnetic particle method for detecting discontinuities in engineering components. This event was recorded in the journal, "Engineering."

Development of Current MT Techniques

Development of the means to establish the magnetic flux in test objects ran in two distinctly separate paths on either side of the Atlantic Ocean. Most American developments used DC storage batteries to produce magnetism in components, whereas the European developments were based on alternating current. These initial preferences are still present in many of the standards and codes, although the DC storage batteries have been replaced with full-wave rectified current.

Advances were also made in the detection media. Instead of using iron filings, iron oxides and iron powders became much more popular, and colored coatings were added to increase the visibility of the indications formed. Later still, fluorescent coatings were applied to the particles, which greatly increased the sensitivity of the inspection process when viewed under "black light" or ultraviolet illumination.

The Present

Today's range of magnetic particle testing techniques is vast and encompasses portable, transportable, fixed, and semiautomatic inspection devices. These use permanent magnets, electromagnets using either AC or DC, or a combination of both. The detection media are available as dry powder or as a suspension in a liquid carrier. They are supplied in many colors so as to provide a contrast with the test surface background color and are also available as fluorescent particles for maximum sensitivity.

II. THEORY AND PRINCIPLES

Introduction

Magnetic particle testing (MT) is a nondestructive testing (NDT) method for detecting discontinuities that are primarily linear and located at or near the surface of ferromagnetic components and structures. MT is governed by the laws of magnetism and is therefore restricted to the inspection of materials that can support magnetic flux lines. Metals can be classified as ferromagnetic, paramagnetic, or diamagnetic.

Ferromagnetic metals are those that are strongly attracted to a magnet and can become easily magnetized. Examples include iron, nickel, and cobalt.

Paramagnetic metals such as austenitic stainless steel are very weakly attracted by magnetic forces of attraction and cannot be magnetized.

Diamagnetic metals are very slightly repelled by a magnet and cannot be magnetized. Examples include bismuth, gold, and antimony.

Only those metals classified as ferromagnetic can be effectively inspected by MT. In order to understand MT, one should have a basic understanding of magnetism and electromagnetism.

Principles of Magnetism

Polarity

Many of the basic principles of magnetism can be deduced by simple observation of the behavior of a magnetized rod and its interaction with ferromagnetic materials, including other magnetized rods. If the rod is suspended at its center, it will eventually align itself with the Earth's magnetic field so that one end points to geographic north and the other end to the south. If the north-pointing end is identified, it will be found that it is always this end that points north. By convention, this end of the rod is called the "north-seeking pole," usually abbreviated as "north pole," and the other end is called the "south pole."

Magnetic Forces

When the north pole of one magnetized rod is placed close to the south pole of another, it will be observed that they attract one another. *The closer they come together, the stronger the force of attraction.* Conversely, if two north poles or two south poles are placed close together, they will repel each other. This can be summarized as *"like poles repel, unlike poles attract."* One way of defining the phenomenon of magnetism could be: "a mechanical force of attraction or repulsion that one body has upon another," especially those that are ferromagnetic

Magnetic Field

The simple observations of attracting and repelling indicate that some force field surrounds the magnetized rod. Although invisible, this force field is clearly three-dimensional because the attraction or repulsion can be experienced all around the rod. A two-dimensional slice through this field can be made visible by placing a sheet of plain white paper over a bar magnet and sprinkling ferromagnetic particles onto it. The particles will collect around the lines of force in the magnetic field, producing an image such as the one shown in Figure 5-1.

This image is called a "magnetograph" and the lines of force are referred to as lines of "magnetic flux." Lines of magnetic flux will flow in unbroken paths that do not cross each other. Each line of force forms a closed loop that flows through and around the magnet. The word "flow" suggests some sort of direction of movement and by convention this direction is said to be the direction that would be taken by a "unit north pole" placed at the north pole of a bar magnet. A unit north pole is an imaginary concept of a particle with no corresponding south pole. Such a particle would be repelled by the magnet's north pole and attracted to the south pole. In other words, magnetic flow is from its *north pole to its south pole through the air* around the magnet and in order to complete the magnetic circuit, flow will be from the south pole to the north pole within the magnet.

Flux Density

The flowing force of magnetism is called "magnetic flux." The magnetograph image does not show the direction of flux flow, but it can be seen from the magnetograph that the *area of maximum flux concentration (flux density) is at the poles*. Flux density is defined as "the number of lines of force per unit area." The unit area referred to is a slice taken perpendicular to the lines of force. Flux density is measured in Gauss or Tesla, the Tesla being the current unit, and flux density is given the symbol "β" (beta).

Magnetizing Force

The total number of lines of force making up a magnetic field determines the strength of the force of attraction or repulsion that can be exerted by the magnet and is known as the "magnetizing force" and given the symbol "H."

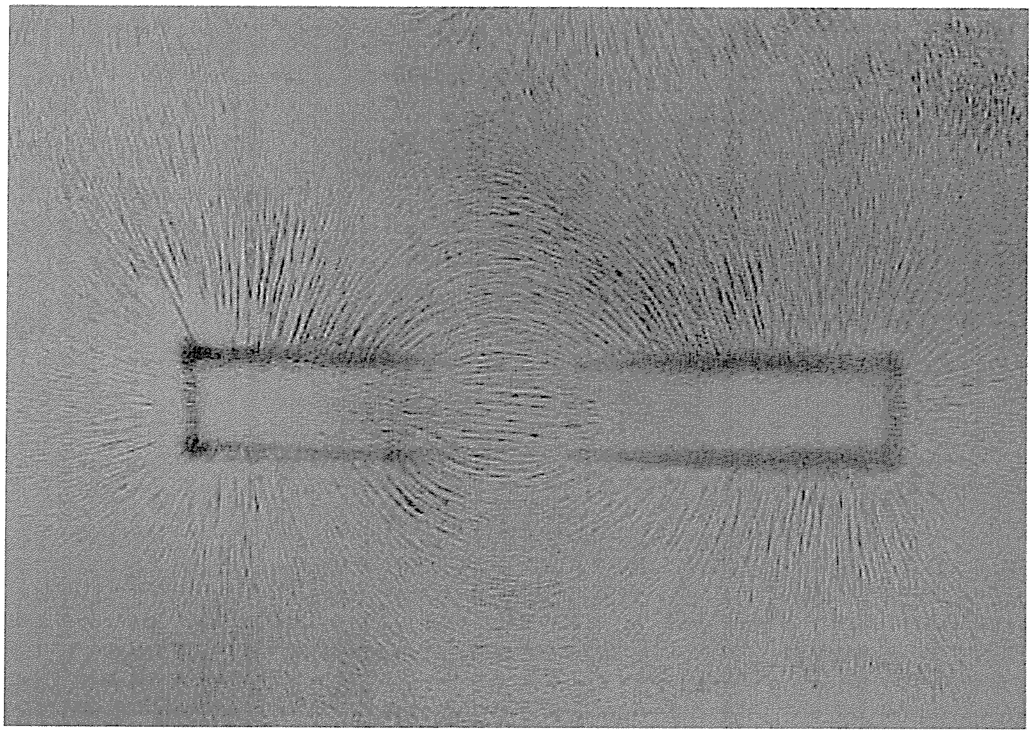


FIGURE 5-1 Magnetograph.

Magnetic Permeability
A German physicist, Wilhelm Weber, postulated a theory about a material's ability to generate or concentrate a magnetic flux field. This theory became known as the magnetic domain theory and relies on an assumption that a magnetic domain is the smallest independent particle within a material that still exhibits a north and south pole (i.e., it has polarity). In an unmagnetized material, these magnetic domains are arranged in a random (haphazard) direction such that their magnetic fields cancel each other out when considering the total magnetic field exhibited by the material.

When a magnetic force is applied to the material, the domains will tend to align themselves with the magnetizing force so that the domains' north poles point in one direction while the south poles point in the opposite direction. The material will now exhibit an overall polarity, which equates to the sum of all of the magnetic domains combined. A flux field will exist around and through the material, as depicted in the sketch in Figure 5-2.

The ease with which the domains align themselves is called "permeability," which is expressed with the symbol "μ" (mu). Materials in which the domains align easily under low magnetizing forces are said to have high permeability. To determine absolute values for permeability, the flux density produced is divided by the magnetizing force applied. Stated mathematically this becomes

$$\mu = \frac{\beta}{H}$$

For practical applications, however, it is far easier to use a comparative measure of permeability, which is determined simply by comparing a material's permeability to that of a

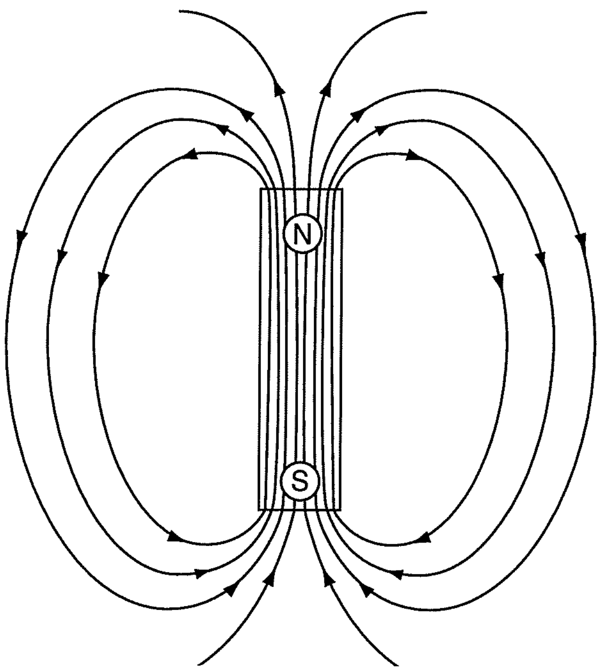


FIGURE 5-2 Magnetograph sketch showing polarity and flux direction.

vacuum. This produces a response that is referred to as "relative permeability" and is given the symbol, "μ_r."

Permeability in magnetic theory can be compared with "conductivity" in electrical theory. Relative permeability can then be compared with the IACS (International Annealed Copper Standard) conductivity scale, in which all conductive materials have their conductivity expressed as a percentage of that of copper. Ferromagnetic materials will have relative permeability values far in excess of one, which is the base value for a vacuum (sometimes referred to as "unity"). They can have values of several hundred times a vacuum's permeability.

Paramagnetic materials in which the domains resist alignment even under high magnetizing forces are said to have low permeability. Paramagnetic materials will have a relative permeability value of slightly greater than 1; for example, 1.003 for some stainless steels.

The third class of metals consists of the diamagnetic materials. The magnetic domains of diamagnetic materials will rotate to positions that are 90° to the direction of the applied magnetizing force, and will create a very slight repulsion to the magnetizing force.

Diamagnetic materials will have a relative permeability value slightly less than one; for example, 0.9996. Paramagnetic and diamagnetic materials are usually referred to as "nonmagnetic" because of their slight or absence of reaction to a magnet.

Magnetic Reluctance

"Reluctance" in a magnetic circuit is the equivalent of resistance in an electrical circuit. The magnetic flux will always follow the path of least magnetic reluctance, which is usually through a ferromagnetic material. The factors affecting reluctance are:

1. The length of the magnetic circuit (λ)
2. The cross-sectional area of the magnetic circuit (A)
3. The permeability of the magnetic circuit (μ)

The reluctance, R, of a given magnetic circuit can be described mathematically as

$$R = \frac{\lambda}{\mu A}$$

Another way of referring to the phenomenon of a material having low permeability is by stating that the material has high reluctance (the domains are reluctant to align themselves).

Magnetic Saturation

The lines of force in a magnetic field repel adjacent lines flowing in the same direction. As the flux density increases, the force of repulsion increases. For a given material there is a maximum value for flux density that can be sustained. Upon reaching this value, the material is said to be "saturated." As the flux density is increased towards saturation, the reluctance of the material increases and the permeability decreases towards that of a vacuum. At saturation, any further increase in magnetizing force finds that the path of least reluctance is now through the air surrounding the material and the excess flux extends out into the air.

Hysteresis

"Hysteresis" describes how the flux density (β) in a magnetic material varies as the magnetizing force (H) is varied. A graphical representation of how flux density increases with an increase in the magnetizing force is shown in Figure 5-3.

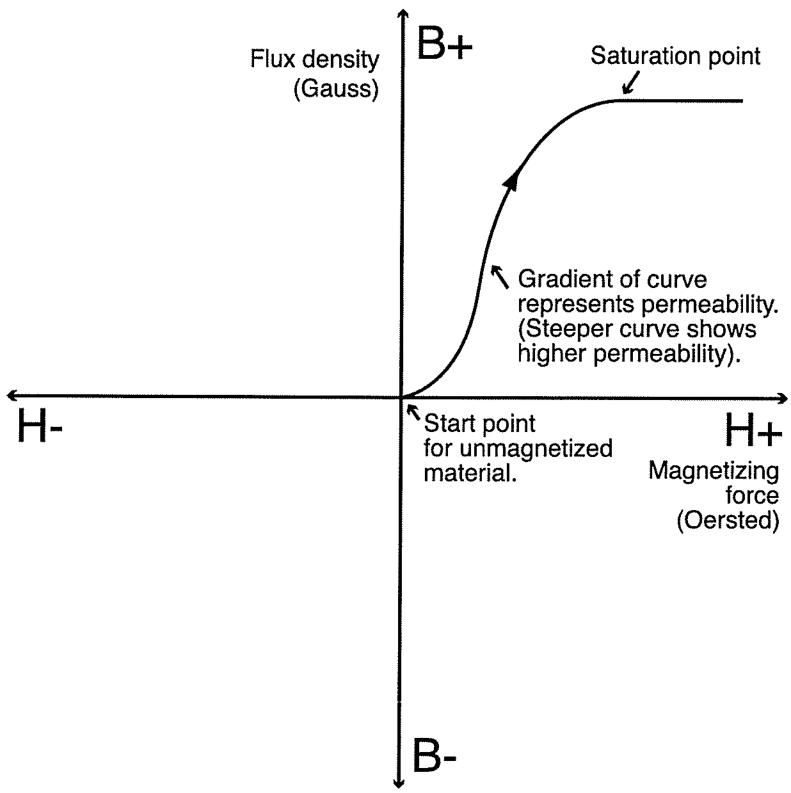


FIGURE 5-3 Hysteresis curve—flux density due to initial magnetization of ferromagnetic material.

From the graph it can be seen that a ferromagnetic material produces a steep initial "virgin curve" due to the relatively small amount of magnetizing force required to produce a high flux density. The flux is being concentrated by the material's permeability. The steepness of the initial "virgin curve" is therefore a measure of the material's permeability.

Also noticeable from the graph is the fact that the ferromagnetic material curve changes in gradient toward the top and will actually flatten out completely at one point. From this point onward, any increase in magnetizing force will not produce an increase in flux density. As mentioned above, this condition is called "saturation." The reason for the change in gradient is due to the reduced amount of magnetic domains available for alignment. The total number of domains present is fixed; therefore, as more of these become locked in alignment due to the magnetizing force, there will be fewer "fluid" domains to create the permeability effect. The relative permeability of a material becomes less as it becomes more magnetized.

The graph shown in Figure 5-3 displays a positive magnetizing force that produces an increasing positive flux density. If the effects of reducing the magnetizing force and plotting the resultant reduction in flux density is considered, even more information about the properties of ferromagnetic materials is gained, as shown in Figure 5-4.

As seen in Figure 5-3, increasing the magnetizing force will increase the flux density until the saturation point is reached. If the magnetizing force is decreased, it will produce a corresponding decrease in flux density. The curve produced by this interaction will deviate from the "virgin curve" produced during the initial magnetization.

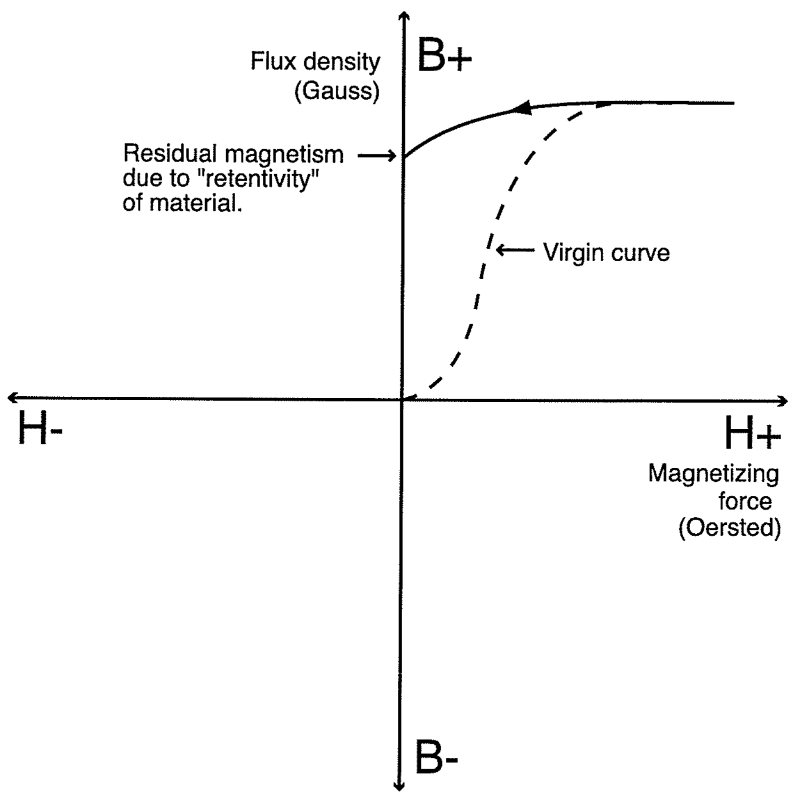


FIGURE 5-4 Hysteresis curve—residual magnetism.

As depicted by the dotted line in Figure 5-5, a point is eventually reached where the magnetizing force is no longer being applied, but there still is a positive flux density in the material.

This phenomenon is due to the "retentivity" of the material, which "retains" some of the flux density and is also referred to as a "remnant field" or "residual magnetism." The amount of residual magnetism will be determined by the retentivity of the material and the amount of magnetizing force initially applied. The retentivity value is highest among the hardened ferromagnetic materials.

Consider what has happened at the magnetic domain level. The domains were initially rotated from their random rest positions by the initial magnetizing force to a position of alignment. When the magnetizing force stops, some of the domains rotate back to a random orientation. Some of the domains, however, remain aligned, resulting in residual magnetism. These domains will remain aligned until a force applied in the opposite direction causes them to rotate back and will actually rotate some of the domains into alignment in the opposite direction.

In Figure 5-5, the effects of applying this opposing magnetizing force can be observed. As this negative force is increased (a force with opposite polarity), the flux density is reduced. The force required to reduce the net flux density to zero is called the "coercive force."

In Figure 5-6, the effects of increasing the opposite magnetizing force beyond the coercive force can be seen. The material exhibits a flux density flowing in the opposite di-

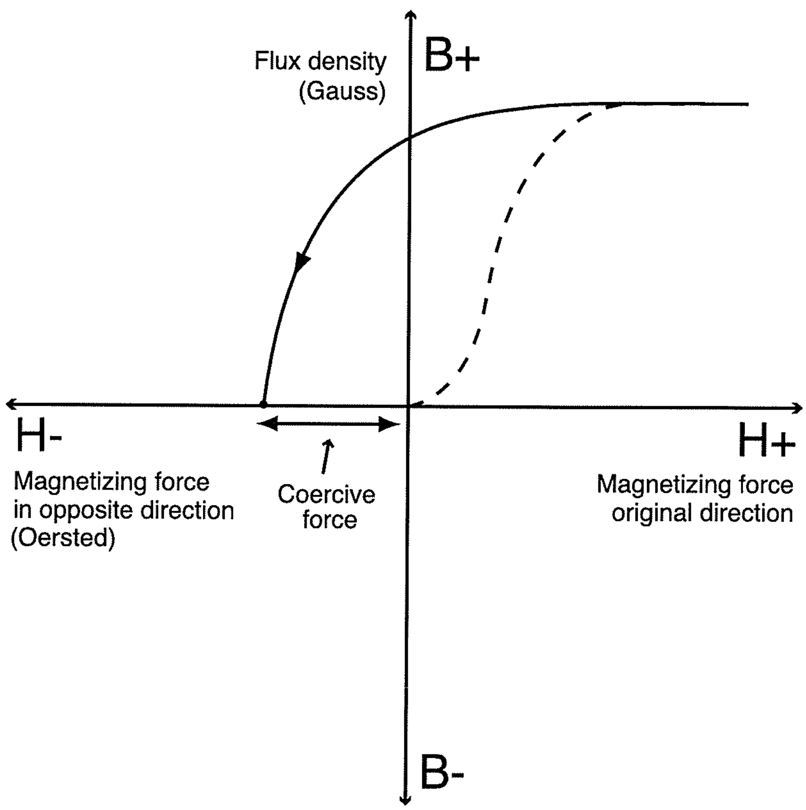


FIGURE 5-5 Hysteresis curve—coercive force.

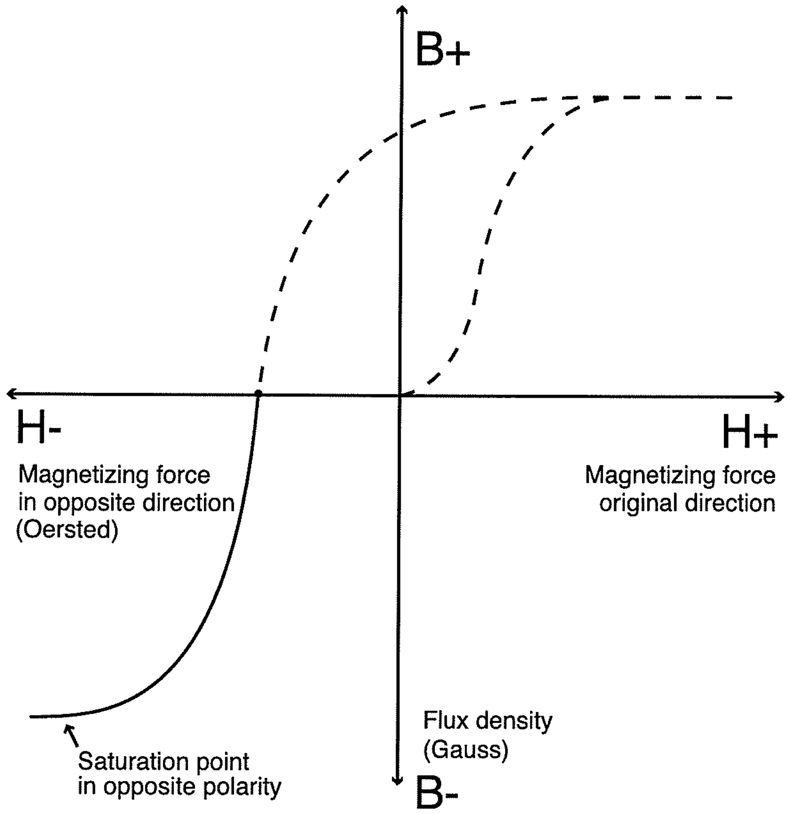


FIGURE 5-6 Hysteresis curve—saturation point with opposite polarity.

rection, which is expressed in the graph as flux density having a polarity opposite to the original. It is also measured in Gauss. The magnetic domains are now rotated such that their north and south poles are aligned 180° out of phase from the initial alignment. A condition is once more achieved whereby all of the domains become aligned in this manner, and saturation occurs in the opposite polarity when all of the domains are aligned.

If this "opposite" magnetizing force is now reduced back to zero, a reduction of the flux density will be observed, but again, some flux density will be present at the point when there is no magnetizing force applied (Figure 5-7).

To eliminate this field and bring the flux density to zero once again, magnetizing force in the original direction must be applied. Again, the amount of force required to achieve zero flux density is called "coercive force" (See Figure 5-8).

A further increase in the magnetizing force will produce an increase in flux density until saturation is once again achieved in the original direction, thereby completing the loop known as the "hysteresis loop" (Figure 5-9). The hysteresis loop can be used to display several of the material's properties. For example, permeability is indicated by the gradient of the virgin curve; reluctance can also be determined from this gradient; a steep curve indicates high permeability, whereas a shallow curve indicates high reluctance.

The residual magnetism is indicated by the flux density value at a magnetizing force of zero. It can be seen in Figure 5-9 that once the virgin curve has been used to produce saturation, the graph continues to follow the "S" shaped hysteresis loop and will never re-

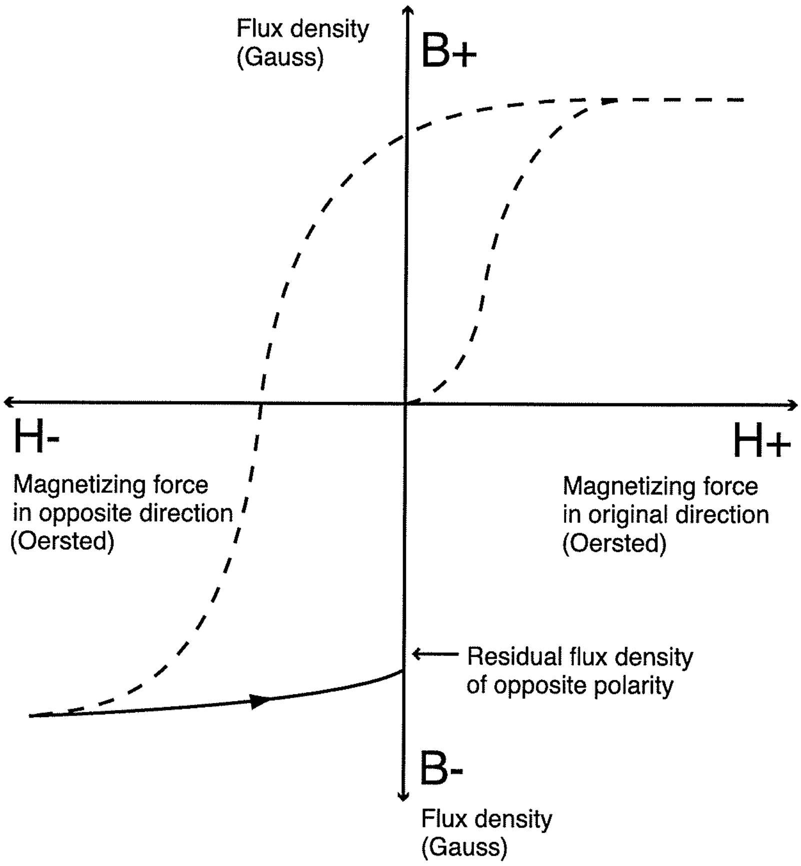


FIGURE 5-7 Hysteresis curve—residual magnetism with opposite polarity.

turns to zero, due to the residual magnetism. This condition will remain until the material is demagnetized.

Magnetization

In the creation of a hysteresis loop, the increase and decrease of magnetizing force was made possible by positioning a powerful permanent magnet closer to or farther away from the object being magnetized. The "negative magnetization" or magnetization in the opposite direction was accomplished by reversing the orientation of the powerful magnet, such that the opposite pole was closest to the object. Magnetism can also be produced by electrical means. If an electrical current flows through a conductor, a magnetic flux will be produced that flows around the conductor and also in the air surrounding that conductor. This flux flows in a circular direction at 90° to the direction of the electric current flow, as shown in Figure 5-10.

Electromagnetic Field Direction

By convention, the actual direction of the flux lines relative to the current flow can be illustrated if the conductor is held in one's left hand. Consider that the electron flow due to the electric current is in the same direction in which the thumb is pointing. The magnetic

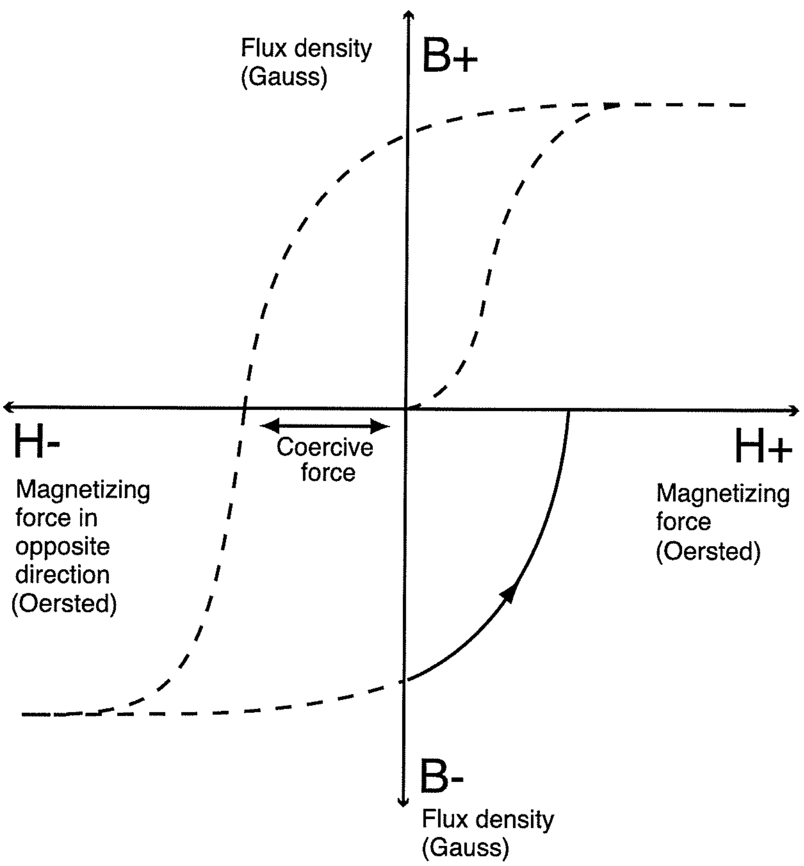


FIGURE 5-8 Hysteresis curve—coercive force with opposite polarity.

flux will flow around the conductor in the same direction in which the fingers are pointing (Figure 5-11).

This "left-hand rule" applies only if it is considered that the "electron flow" is from negative to positive. This is a relatively recent belief. The original "electric current flow," concept given by French physicist Ampere was that the current flowed from positive to negative. If this were the case, then the "right hand rule" would apply.

If the conductor were the actual ferromagnetic test object, concentrated circular flux lines would be produced in the object. The magnetization of a part in this way is referred to as "direct" magnetization. Current is passed directly through the part, creating the circular flux field.

If a non-magnetic conductor were formed into a "loop," the magnetic flux circulating in the air around and through the loop would be as shown in Figure 5-12. It can be seen that at the center of the loop, the flux is basically linear. This effect becomes more pronounced if the conductor is wound into several loops close together so as to form a coil. If the turns of the coil are close enough to each other, the individual flux fields from each loop will join together to create a field for the whole coil (see Figure 5-13).

When a ferromagnetic object is placed inside this coil, flux lines are induced into the object, resulting in a longitudinal flux field in the object in approximately the same direc-

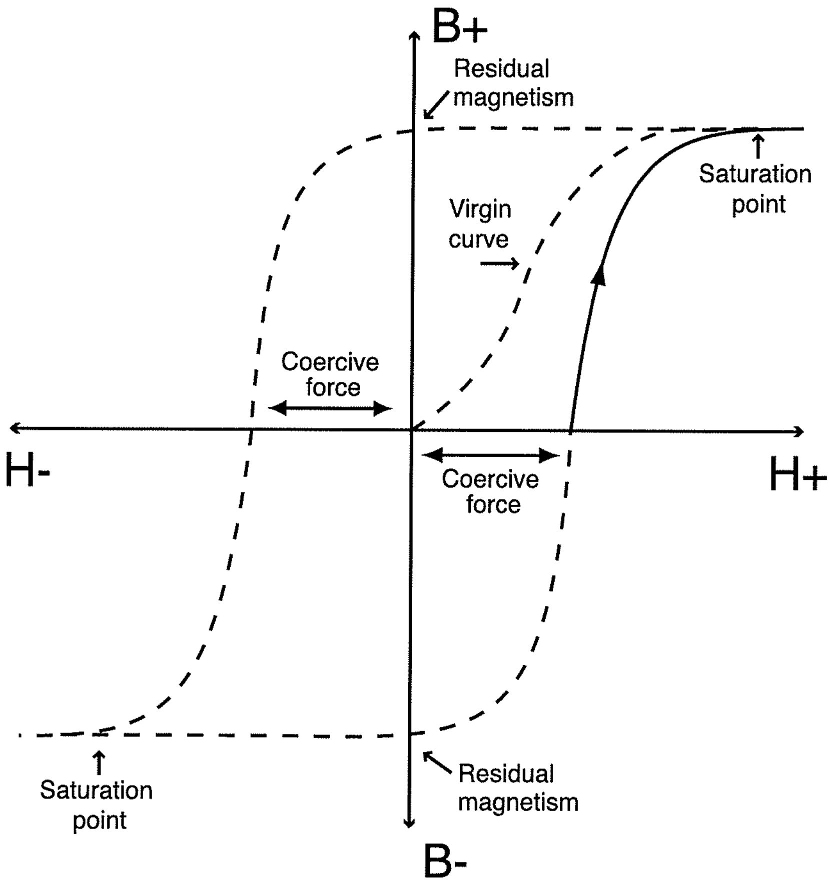


FIGURE 5-9 Hysteresis curve—completed hysteresis loop.

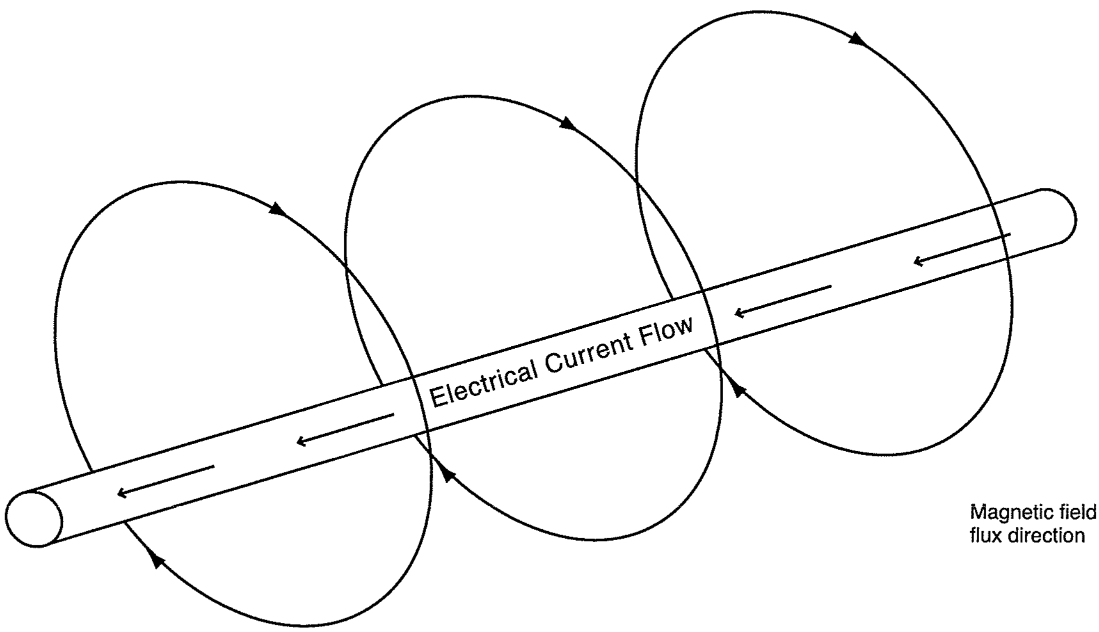


FIGURE 5-10 Flux lines around a current carrying conductor.

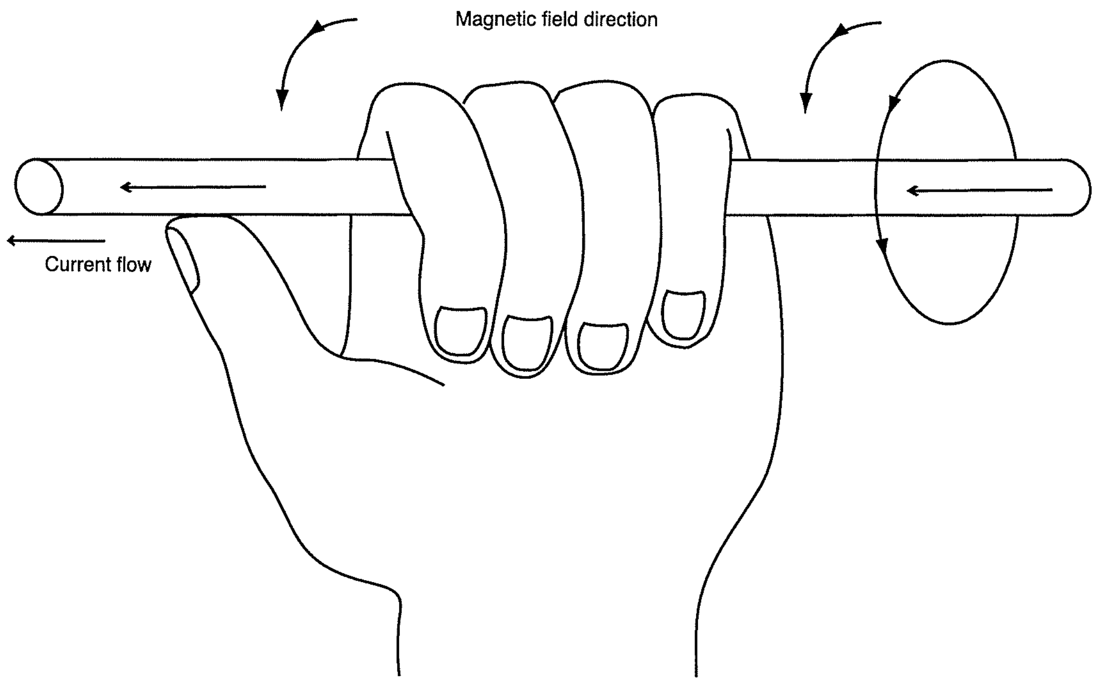


FIGURE 5-11 Flux line direction based on the left hand rule.

tion as the coil axis. Magnetization of a part within a coil is accomplished by magnetic induction and is referred to as "indirect" magnetization. It is therefore possible to produce both circular and longitudinal magnetic flux fields in the test object using electromagnetism.

Detection of Discontinuities

Distorted Fields

The lines of force in the internal field of a magnetized material will tend to distribute themselves evenly through the material, provided that the material is homogenous. The presence of a discontinuity presents an interruption to the field and an increase in reluctance. The lines of force prefer the path of least reluctance and will therefore redistribute themselves in the material by bending around the discontinuity. The field becomes "distorted" by the discontinuity.

Leakage Fields

As a discontinuity gets larger, the remaining metal path in the part becomes more restricted and the magnetic flux approaches saturation for that part of the material. Some of the magnetic lines of force then find that a path through air or across the discontinuity presents a lower reluctance than the remaining metal. As a result, some flux lines "break out" of the surface of the metal into the air. This is called a "leakage field." It is interesting to note that a leakage field may exist both at the near surface and also at a remote or hidden surface.

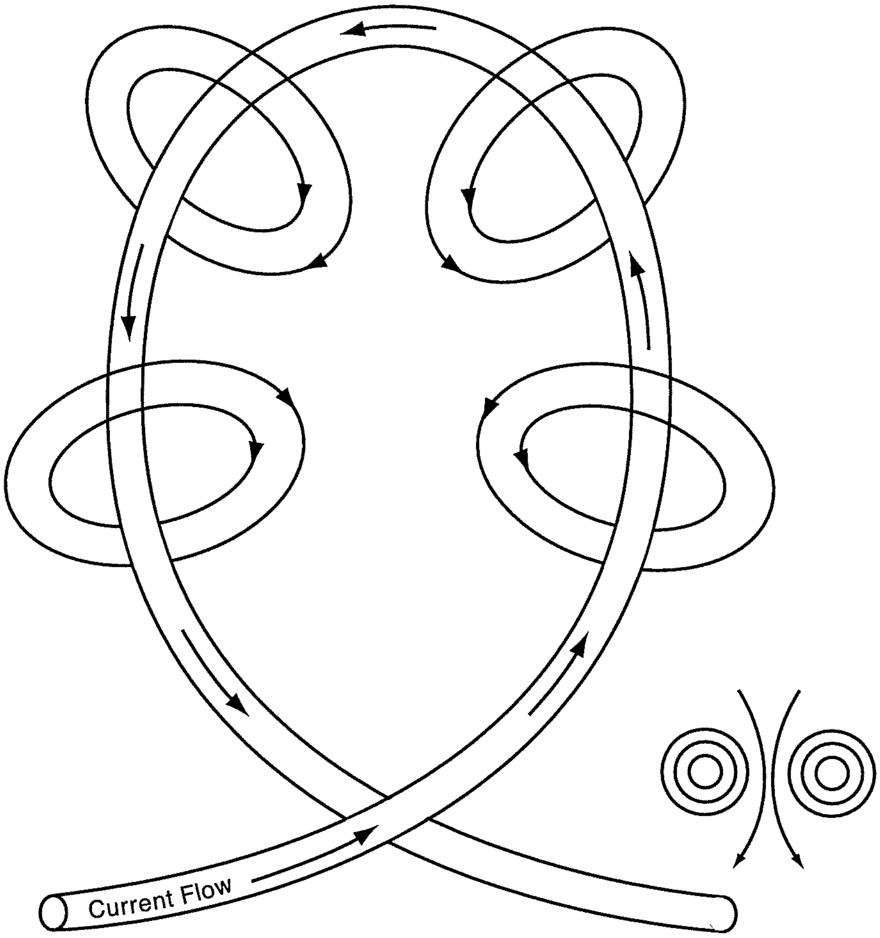
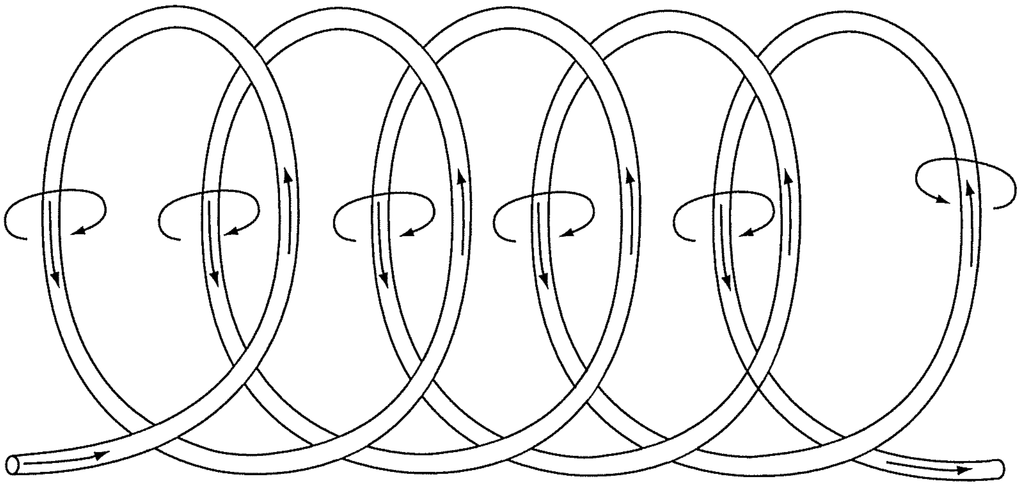


FIGURE 5-12 Current flowing in a coil showing flux lines produced.

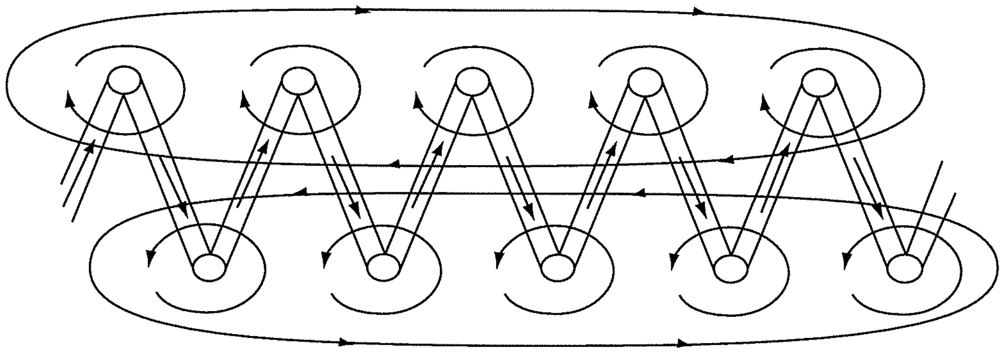
In order to create a leakage field, the discontinuity must interrupt the lines of force in the material. A narrow discontinuity oriented parallel to the flux lines will not create a leakage field. In order to produce a leakage field, a discontinuity must interrupt the field usually considered to be within 45° to the perpendicular. It follows that in order to detect a discontinuity with any orientation, the part must be magnetized in at least two directions, 90° to one another.

Making the Leakage Field Visible

When a flux leakage field occurs, a north and south pole will be created at that location (see Figure 5-14). It has already been established that the maximum flux density will occur at the poles. Therefore, whenever a discontinuity disrupts the flux lines and flux leakage occurs, an area of high flux density will be produced. When ferromagnetic particles are applied to the surface of the test object, they are strongly attracted to this flux leakage area and will form an accumulation of particles, producing a visible indication of that discontinuity (see Figure 5-15). The creation of an indication relies on the flux lines being distorted sufficiently to produce flux leakage.



(a)



(b)

FIGURE 5-13 (a) Current in a multiturn coil and combined flux lines produced. (b) Plan view of a multiturn Coil.

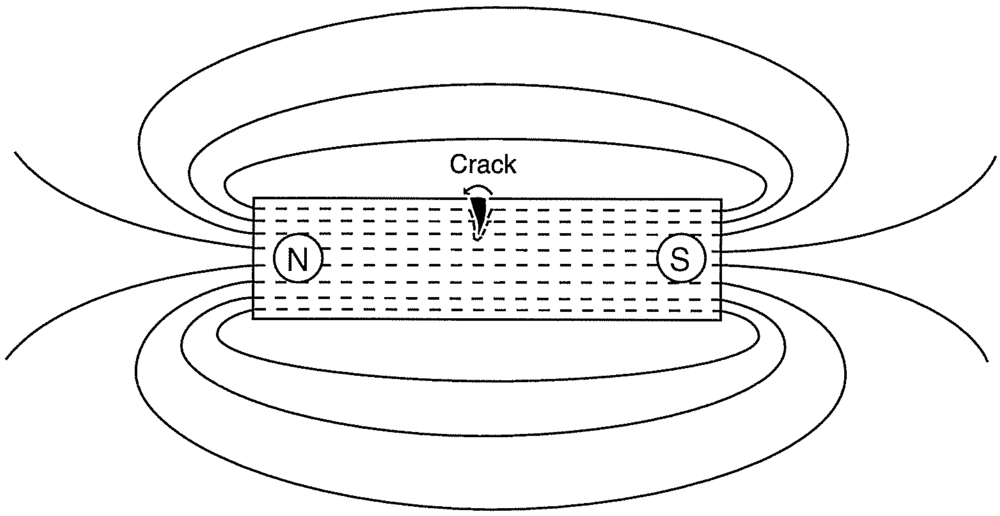


FIGURE 5-14 Flux distortion and leakage field at a crack.

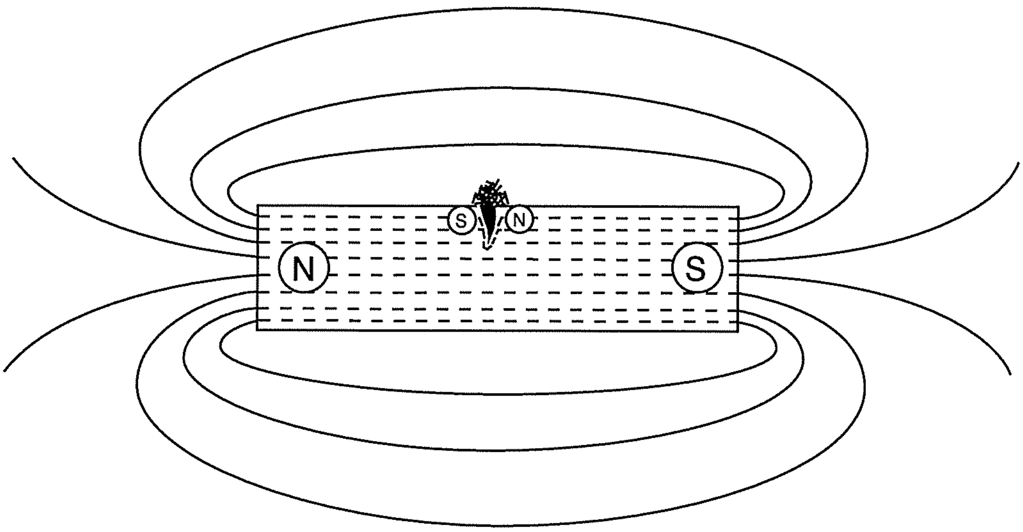


FIGURE 5-15 Particles applied.

Part Geometry
Some aspects of the part's geometry may also produce flux leakage. For example, threads, keyways, or other abrupt changes in section thickness will cause flux leakage and produce indications referred to as "nonrelevant" (see Figure 5-16).

Control of Magnetization
The dimensions of the discontinuity in relation to the component thickness, together with the strength of the applied magnetizing force, will determine the strength of the leakage field. When the component has a complex geometry, no one value of magnetizing force

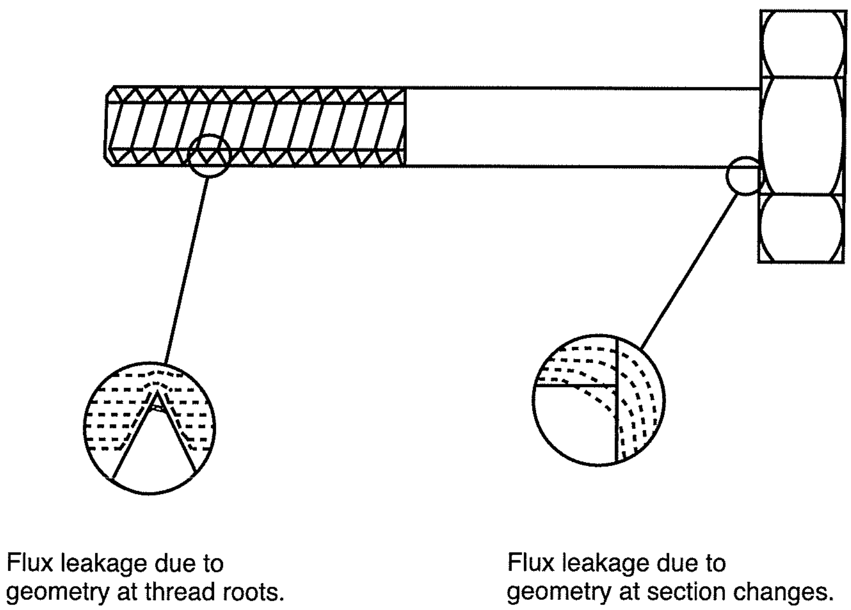


FIGURE 5-16 Flux leakage at threads and geometric changes.

will be suitable if nonrelevant indications from section changes are to be avoided. It is therefore necessary to control the magnetizing force to suit the geometry of the part. With electromagnetism, there is far greater control than with permanent magnets. By varying the applied current, the magnetic flux density produced can be controlled to minimize nonrelevant indications while still complying with inspection requirements.

Types of Electrical Current

Direct Current (DC)

Current produced from a battery is constant in amplitude and direction and is called "direct current" or DC. A graphical representation of DC field is illustrated in Figure 5-17.

Altenating Current (AC)

Current provided from a conventional electrical outlet constantly varies in amplitude and also reverses in flow direction (polarity) many times a second. It begins at zero and flows in one direction, rising from zero to maximum flow, then decreases back to zero before reversing in flow direction, rising from zero to a maximum flow in the opposite direction before falling back to zero once again to complete a full cycle. The actual number of cycles per second is called "frequency." The frequency of AC power in the United States is 60 cycles per second or 60 "hertz" (1 hertz = 1 cycle per second). A graphical representation of this cycle is shown in Figure 5-18. This type of current is referred to as "alternating current" because it is continuously alternating in direction.

Half-Wave Rectification

This alternating current can be modified in several ways. Its frequency can be altered by using an oscillating circuit (although this is seldom done in MT) or the "negative" portion of the current flow can be removed to allow the current to flow only in one direction. This

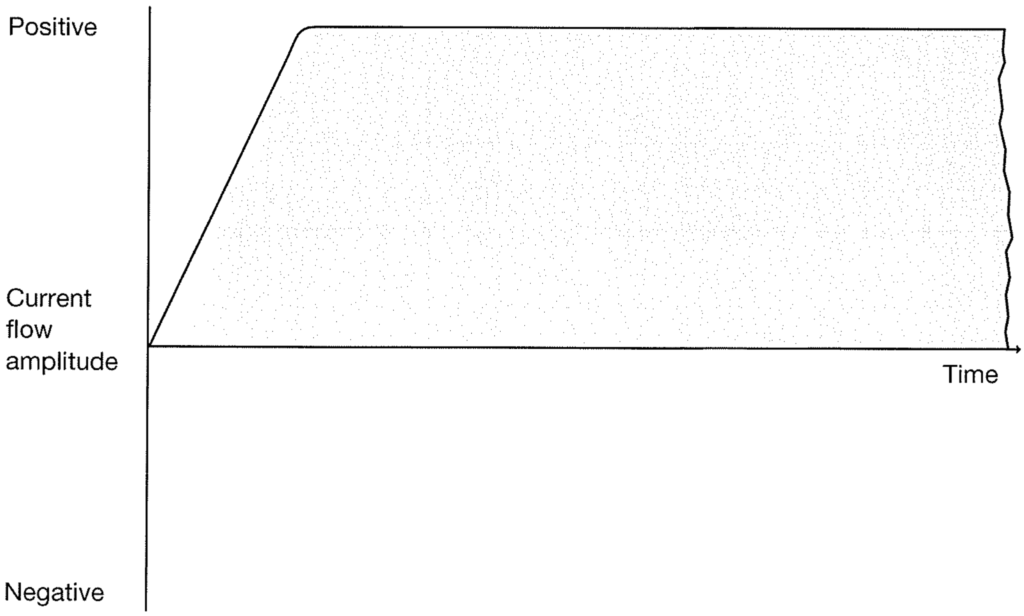


FIGURE 5-17 Graphical display of direct current waveform.

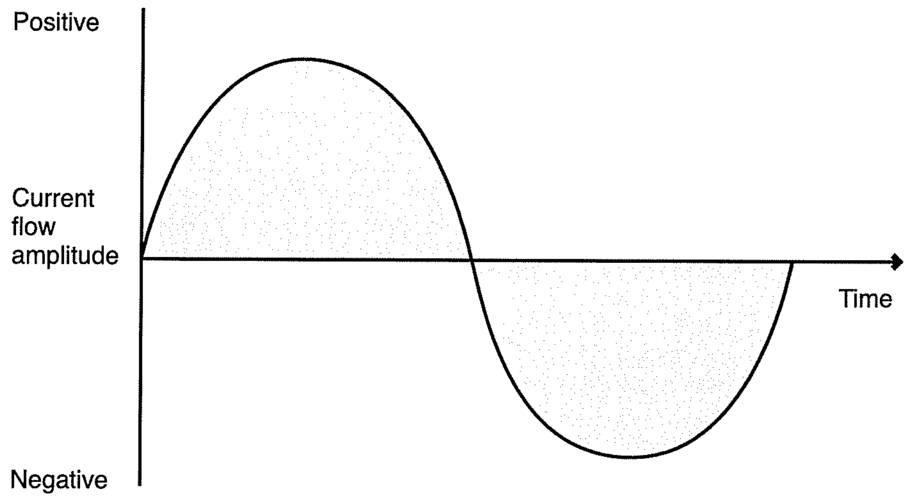


FIGURE 5-18 Graphical display of alternating current waveform.

is called "half-wave rectified" alternating current (HWAC) and its effects on the waveform can be seen in Figure 5-19. Obviously, if half of the electrical current is removed, this will reduce the magnetic flux produced.

Full-Wave Rectification

One other alternative is to reverse the polarity of the negative portion of the wave to make it also positive. This is called "full-wave rectified" (FWAC) alternating current and it causes little or no loss of the original AC wave's power (see Figure 5-20).

Electrical Power

The power developed in an electrical circuit is measured in watts (*W*) and is the product of the applied voltage (V) and the resulting current (I):

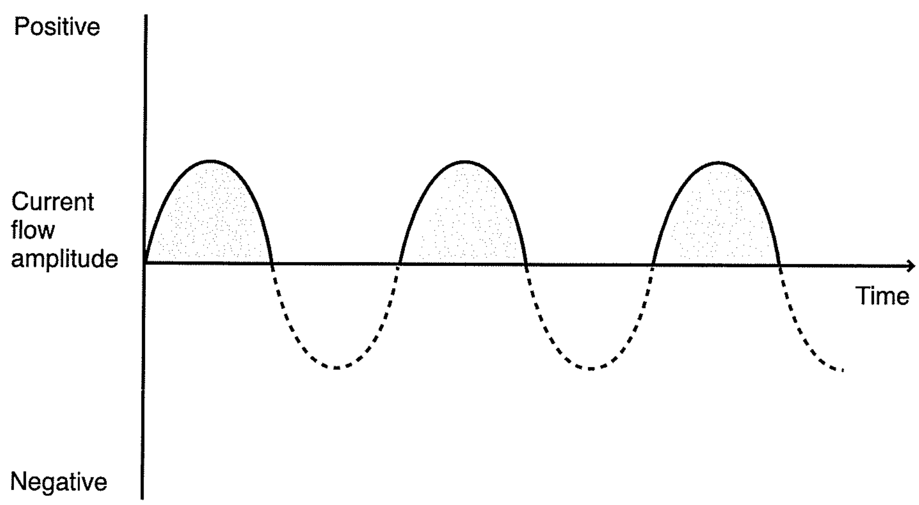


FIGURE 5-19 Graphical display of half-wave rectified (HWAC) current.

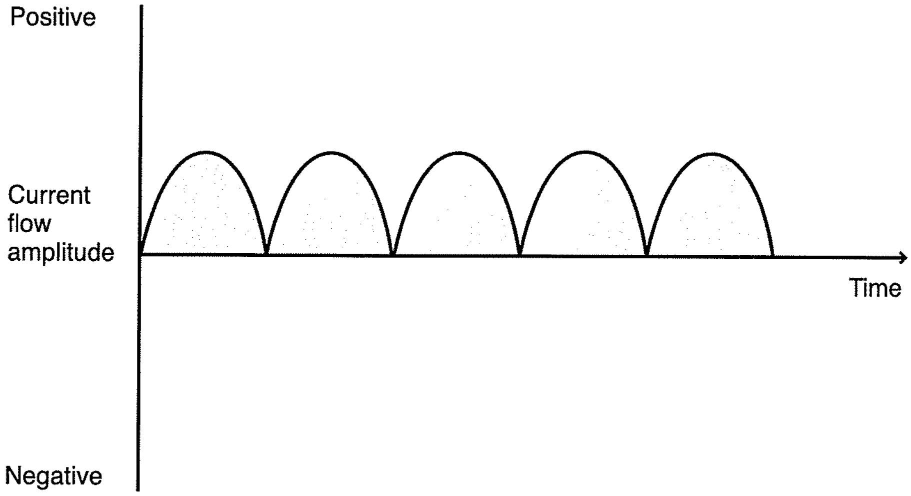


FIGURE 5-20 Graphical display of full-wave rectified (FWAC) current.

$$\text{Watts} = V \times I$$

One of the byproducts of the current developed is heat, which may damage metals if the current is applied for an extended period of time. At the same time, the flux density achieved with electromagnetism is proportional to the current flowing. These two factors need to be balanced when selecting the magnetizing parameters for MT. For safety reasons, most MT equipment operates at a low voltage (typically 3 volts), and so the current is the greater contributor to the power in the circuit.

The electrical current amplitude is measured in amperes (amps). With DC, the amplitude is constant; however, with any of the sinusoidal wave forms produced by AC, half-wave or full-wave rectified, the "peak" amperage produced at the maximum flow rate at the peaks of the waves will only apply for an instant. The average current includes the zeros, the peaks, and all points in between. The average value for an AC wave or full-wave rectified AC will be approximately 70% of the peak value. This value is referred to as the "root mean square" (RMS). It can be seen that the power developed at 1000 amp DC will be higher than at 1000 amp AC. With half-wave rectified AC, the difference becomes much more pronounced because half of the AC wave is not used; therefore, the actual output will only be approximately 35% of that produced by DC.

Care should be exercised when setting amperage values based on meter readings. Some meters indicate peak values and some will indicate RMS values.

With three-phase current, when the AC wave is one-third into its cycle, a second wave is generated; and when the second wave is one-third into its cycle, a third wave is generated. The result is three AC waves being generated simultaneously, with each one overlapping the others, thus providing more current flow and a smoother distribution. See Figure 5-21.

Early versions of MT equipment required banks of batteries to produce pure direct current. These were cumbersome and long charge cycles to produce relatively few "shots" before recharging again were necessary. Equipment with DC capability relies on modifying AC current into DC by full-wave rectification. This is further enhanced by using smoothing capacitors to slow down the rate of decay of the peaks and help to "fill in" the troughs. If three-phase current is used with full-wave rectification, this smoothing of

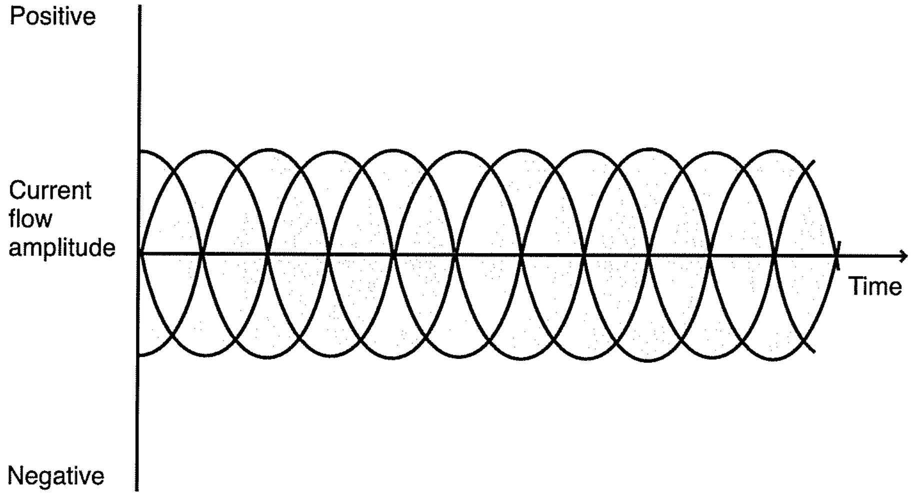


FIGURE 5-21 Graphical display of three phase wave AC.

the waveform and current flow is improved to a point where almost pure DC results (see Figure 5-22).

The Influence of AC and DC Currents
In addition to the amount of flux produced, the different currents used will affect the distribution of the flux in the part.

With DC, the current tends to use the entire cross section of the conductor, decreasing to zero at the center. The lines of magnetic force tend to spread through the material thickness and similarly decrease in density toward the center. With any of the AC wave forms, the current and lines of force tend to be confined to a region close to the surface of the material. The depth of penetration of both depends on the frequency of the AC. For 60 hertz this depth is roughly 3 mm (0.125″). This phenomenon is called the "skin effect." The higher the AC frequency, the shallower the depth of penetration.

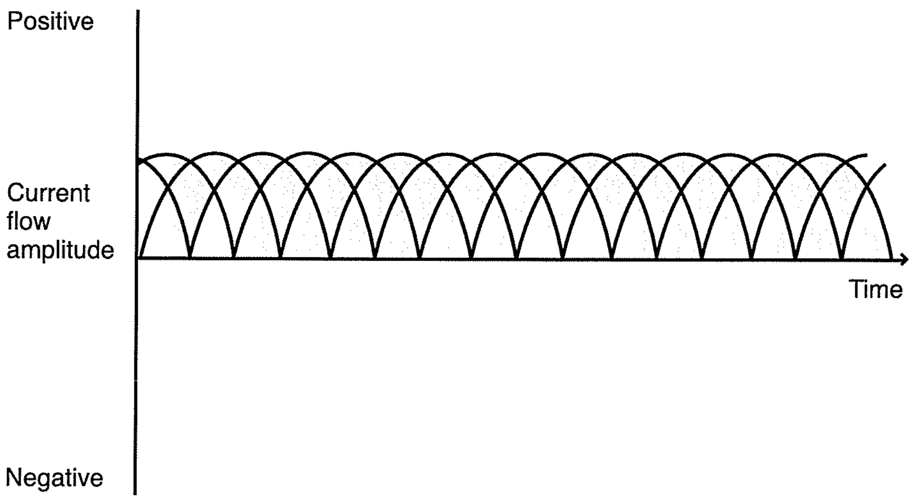


FIGURE 5-22 Graphical display of three phase full-wave rectified AC.

This difference in flux distribution can be used to an advantage. If it is desired to detect discontinuities slightly deeper in a part, then DC will result in a greater penetration of the flux. If the goal is to detect surface discontinuities, the concentration of the flux at the surface due to the skin effect will enhance detection. It is for this reason that DC is preferred for the detection of manufacturing induced discontinuities, which may occur anywhere in the part. The deeper the discontinuity is below the test surface, the broader and less distinct the indication becomes. To enhance the contrast it is necessary to use dry particles, since the particles are larger than those used in a suspension. The larger particles are also less mobile and more reluctant to gather at the region of the flux leakage, so that some form of external agitation may be required (blowing on the surface or tapping the component). Also, the amperage required to achieve sufficient flux density using DC will be higher than for AC and this will increase the heating effect. Before deciding to use DC current for deeper penetration, it may be worth considering whether another NDT method would be more suitable.

AC current is preferred for the detection of surface and near-surface discontinuities, particularly during in-service inspection, where discontinuities, by nature, tend to be surface-breaking (e.g., fatigue cracks). For a given current, the flux density near the surface is higher when using AC and this means that lower currents than those required for DC can be used. This, in turn, produces less heat. Another advantage is that an AC field, by its cyclic nature, tends to vibrate the particles, thereby increasing their movement toward the area of flux leakage. Most users regard magnetic particle testing as a method for the detection of surface and near-surface discontinuities only.

Detection Media

The detection media used for MT are basically similar to the ferromagnetic particles used in producing a magnetograph; however, they are of a higher level of refinement. Their size and shape are carefully controlled to produce a variety of different sizes and shapes. Different shapes are desired to meet different aspects of indication formation. Elongated particles will rotate to align with the flux lines, due to their increased length-to-diameter ratio, whereas rounded particles have greater mobility to move to the areas of flux leakage.

Different sizes are necessary. The smaller particles have the ability to accumulate at small discontinuities and produce a sharper indication. This is often useful in identifying the nature of the discontinuity. For example, a crack indication will have a jagged appearance. Larger particles have the ability to bridge across larger discontinuities and increase contrast.

Particles may be applied in a dry form or may be suspended in a liquid such as kerosene or a similar petroleum distillate. They may also be suspended in a water carrier containing suitable additives such as wetting agents, and antifoam liquids.

The particles used in the wet suspensions are usually iron oxides as opposed to iron filings, due to their lighter weight and greater ability to remain in suspension. The disadvantage of using iron oxides is the reduced permeability of the oxides compared to iron filings. This results in a lesser response to the weaker leakage fields produced by subsurface discontinuities. A distinct advantage of using suspended particles is their greater mobility in the liquid, which improves the detection of small surface discontinuities. Whenever the wet suspension is used, it is essential that periodic checks be made to determine the particle concentration in the liquid carrier. This is referred to as the "settling test" and will be discussed in detail at the end of Section IV.

The visual impact of indications is also assisted by the addition of a coating to the particles to provide a greater contrast with the test surface. This results in a significant increase in "seeability" or sensitivity. The coatings fall into two distinct groups, color contrast and fluorescent.

Color contrast coatings are available in several colors, including blue, red, gray, and black. See Figure 5-23 for examples of dry particles. The choice of color depends upon the color of the test surface and the degree of contrast to be provided. If suitable contrast cannot be achieved, another possibility is to coat the part with a specially formulated white contrast paint, which is quick drying and easily removed after inspection by using a solvent. This will create a good contrast between the black particles in a liquid carrier and the white background (see Figure 5-24.)

The fluorescent particles are viewed under black light illumination in a darkened viewing area. The fluorescent particles emit light when activated by the black light, providing excellent contrast against the dark background of the part due to the darkened viewing conditions. (See Section III for more information about black lights).

Demagnetization

Demagnetization of the test part is sometimes necessary before, during, and at the end of an inspection, for a variety of reasons. The principal reasons are described below.

Before and During the Test

If the test part has been left with a residual field in a different direction to the field about to be applied, the resulting field will be the vector sum of the residual magnetism and the

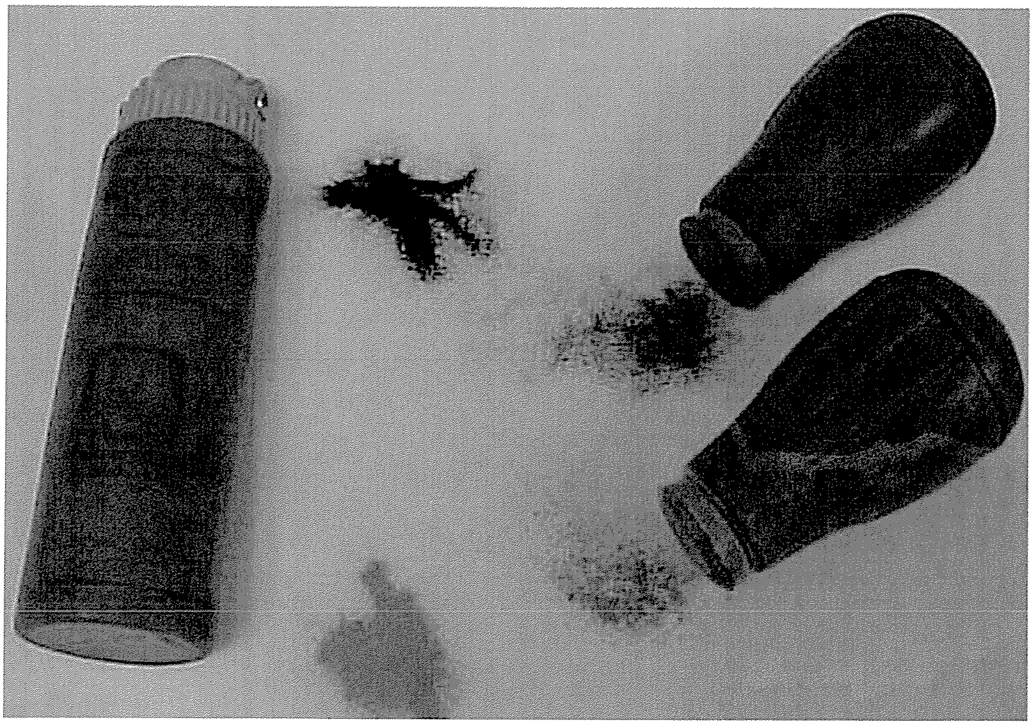


FIGURE 5-23 Examples of dry particles.

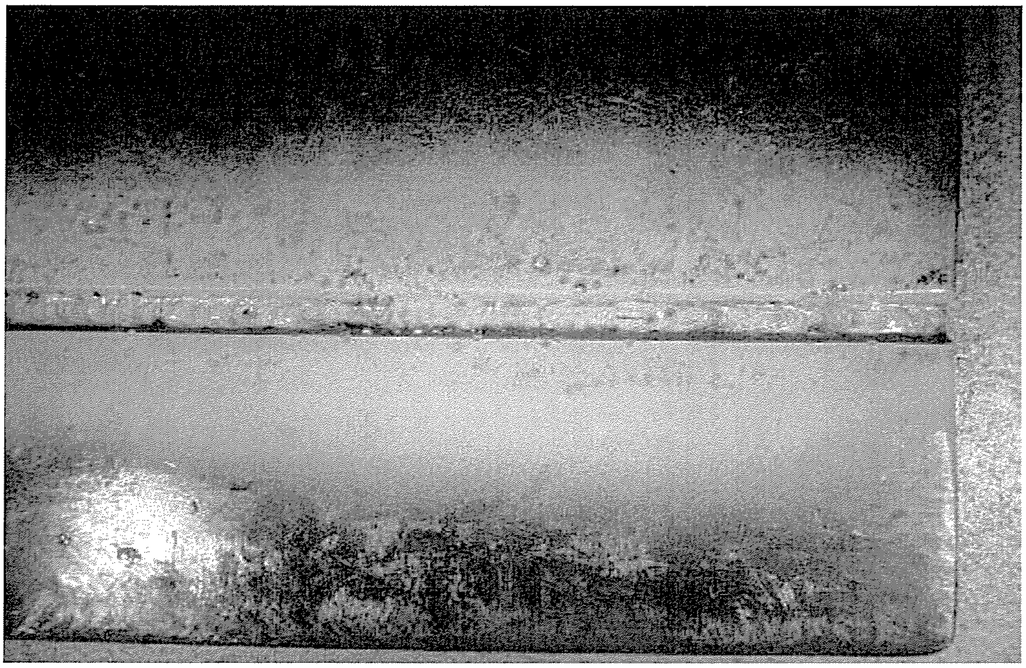


FIGURE 5-24 Weld with white contrast paint.

newly applied field. The direction of the resulting field will therefore not be precisely in the direction intended; therefore, sensitivity may be reduced. Demagnetization is recommended in this case.

After the Test

A residual field in a component being returned to service may have a detrimental effect on future operations of the part or nearby equipment. In an aircraft or ship, a compass may be affected. High-speed rotating parts may induce eddy currents in nearby structures, causing a braking effect on the part and heating of the surface. If the part is to be welded after inspection, the residual field may deflect the weld arc and make it difficult to control the weld deposit.

Demagnetization Process

In order to effectively demagnetize a part, two requirements must be met:

1. The polarity must be successively reversed
2. The field strength (flux density) must be decreased

This means that each successive current application will be in the opposite direction to the previously applied force and will be at a lower level. It should be below the saturation point, but must be above that required to produce a higher flux field than retained. This will produce successively lower residual fields at each application until an acceptably low field exists. It should be noted that although total demagnetization will not result, the field can be brought to an acceptable level.

These two requirements can be met using a reversing DC field; however, AC is preferred, due to its inherent reversing nature. The most satisfactory method of demagnetization using AC is to gradually reduce the applied current to zero or, more commonly, to pass the test part through an AC demagnetizer.

One way to completely demagnetize is by heating the part to a temperature above its curie point and allowing it to cool without any magnetizing force acting upon it. If this can be accomplished, the residual field will be totally removed and the part will be totally demagnetized. The curie points for steels range from 720 °C (1296 °F) to 800 °C (1440 °F). For most NDT applications however, this approach is not practical.

III. EQUIPMENT AND ACCESSORIES

Different MT equipment is available for production line and field-type applications. To facilitate the varied applications, several basic groups of test equipment are available. They are classified as "stationary," "mobile," or "portable" units.

Stationary Units

A stationary unit is referred to as a wet horizontal unit and usually has capabilities for producing longitudinal and circular fields. Some units will also be capable of demagnetizing the parts, although this is usually accomplished with a separate demagnetizer. Figure 5-25 illustrates a typical wet horizontal stationary unit. This unit has a fixed headstock

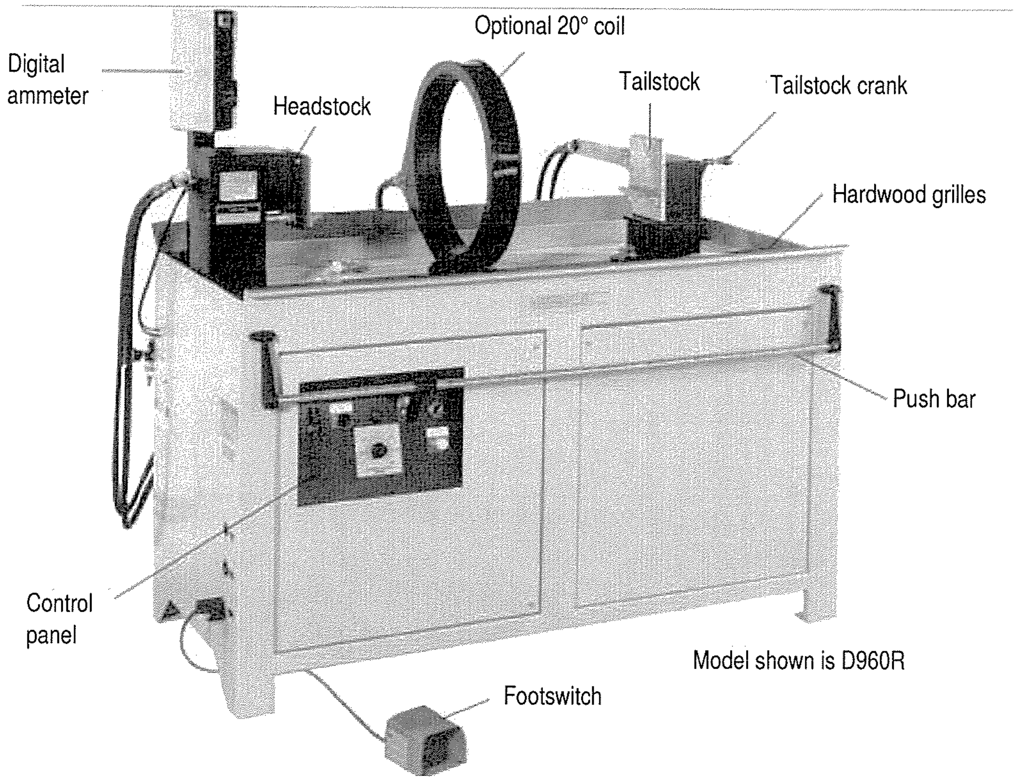


FIGURE 5-25 Wet horizontal unit.

and a sliding tailstock. The part is placed between these and the tailstock is adjusted to just slightly longer than the length of the part. When the tailstock is locked in this position, a foot-switch controlled, pneumatic headstock closes and grips the part tightly to permit the current to flow, thereby producing a circular magnetic field.

If hollow parts such as tubular products or ring-shaped parts are to be inspected, a central conductor technique can be used. This involves the use of a bar of high electrical conductivity, typically copper or aluminum, that is gripped between the headstock and tailstock. When current is passed through the conductor bar, a circular magnetic field will be induced in the component. It should be noted that the flux density in the part will be highest at the inner surface. Advantages of this technique are that several components may be inspected simultaneously and there is no risk of overheating the parts or arcing between the unit and the part(s) (see Figure 5-26), since this is an indirect magnetization technique.

For longitudinal magnetization techniques using coils (as in Figure 5-25), the part can either remain in this position if a centralized coil position is used or it can be placed on the lower inside surface of the coil. The ratio of coil inner diameter to component outer diameter, or cross-sectional area ratios, will determine which position should be used. This will vary based on specification requirements.

The amperage can be adjusted using a variable self-regulating current control. An adjustable timer controls the current duration. Demagnetization is accomplished using either the coil in the wet horizontal unit or a separate AC coil demagnetizer. The stationary units are very versatile in their range of capabilities; however, the main limitation is their inability to be taken to a field location. For this, "mobile" or "portable" equipment must be used.

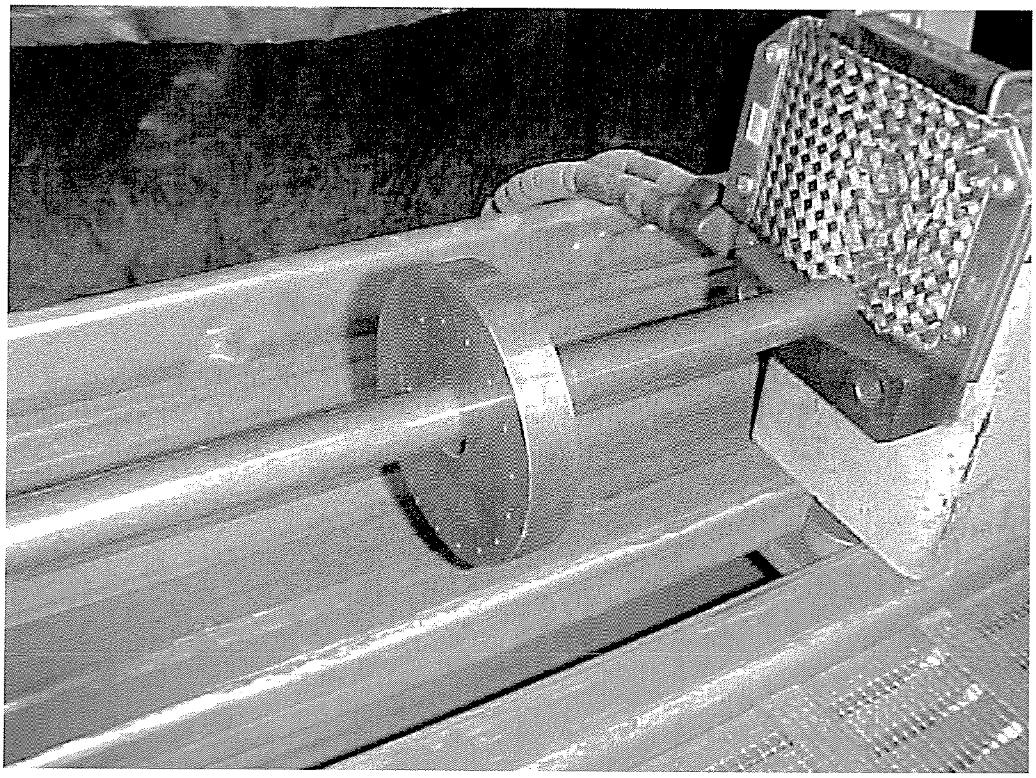


FIGURE 5-26 Central conductor setup with a Keytos ring.

Mobile and Portable Units

The main difference between mobile and portable equipment is in their ability to be moved. A mobile unit must be transported to a location, then moved around on its own wheels or castors (see Figure 5-27). It can weigh up to 1000 lbs (500 Kg). A portable unit can usually be carried by one person, and will probably weigh no more than 50 lbs. (25 kg) (see Figure 5-28).

Despite their size difference, both of these types of units can accomplish similar inspections with the use of various accessories. The power outputs of these units vary considerably. As expected, the mobile unit will have a much higher output than the portable unit. Some of the mobile units can produce as much as 6000 amps, whereas the portable units are usually limited to a maximum of 1500 amps.

Common accessories include clamps and prods for producing circular magnetization. Great care must be exercised when using prods or clamps to ensure that good contact is maintained with the test specimen, otherwise electrical arcing can result. This can produce localized areas of surface damage and potential stress risers in the part.

Cable wrapped coils and rigid coils are used with the mobile and portable units for producing longitudinal magnetization. Both mobile and portable units usually have selectable AC or DC positions, which also enables demagnetization to be accomplished.

Electromagnetic Yoke

Even greater portability can be achieved by using an electromagnetic yoke, which is referred to as an AC yoke or contour probe (see Figure 5-29). This unit can be used with AC and is also available in a battery pack version, which further increases its portability by eliminating the need for an AC power source. Many yokes have articulating legs to facilitate various inspection area profiles. These yokes produce only longitudinal magnetization; repositioning is required to achieve flux line orientation in at least two 90° opposing directions.

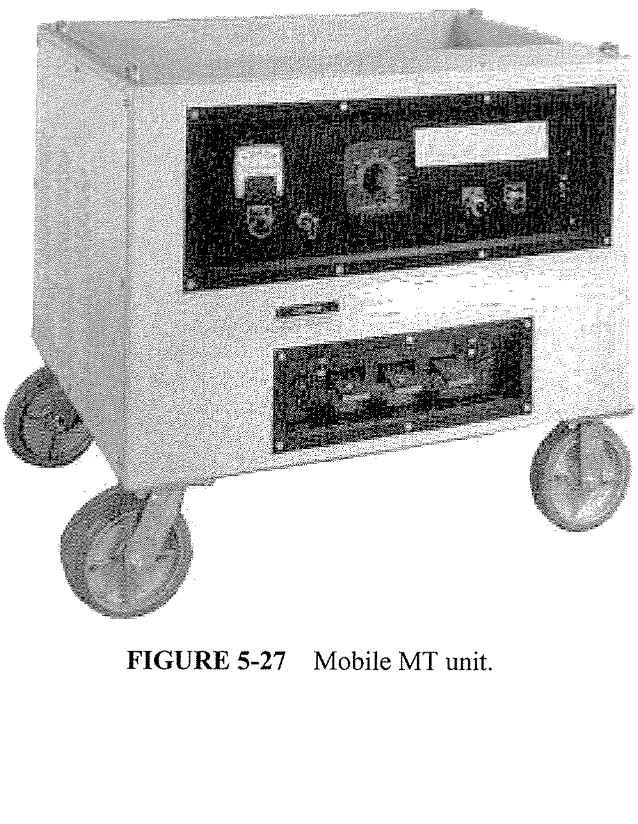


FIGURE 5-27 Mobile MT unit.

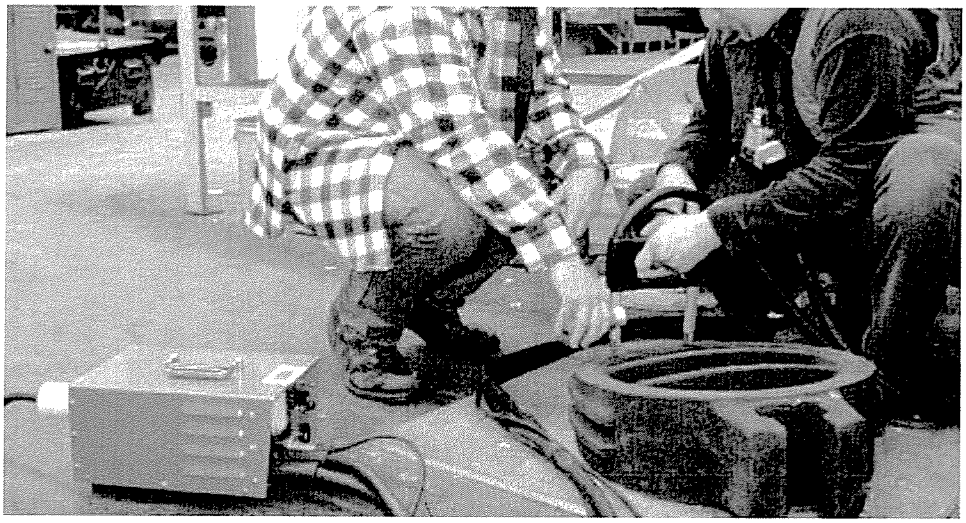


FIGURE 5-28 Portable DC prod unit.

Permanent Magnets

Small permanent magnets can also be used to produce localized longitudinal magnetization, but there are some limitations to their use (see Figure 5-30). Due to their strong fields, particles tend to become attracted to the legs more readily than the test surface. At times, the use of these magnets can become unwieldly.

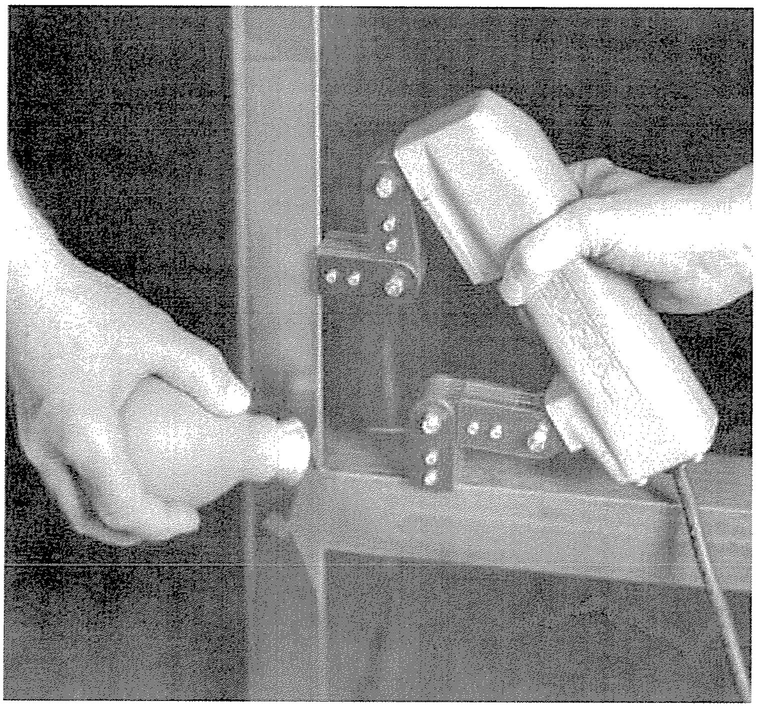


FIGURE 5-29 AC yoke.

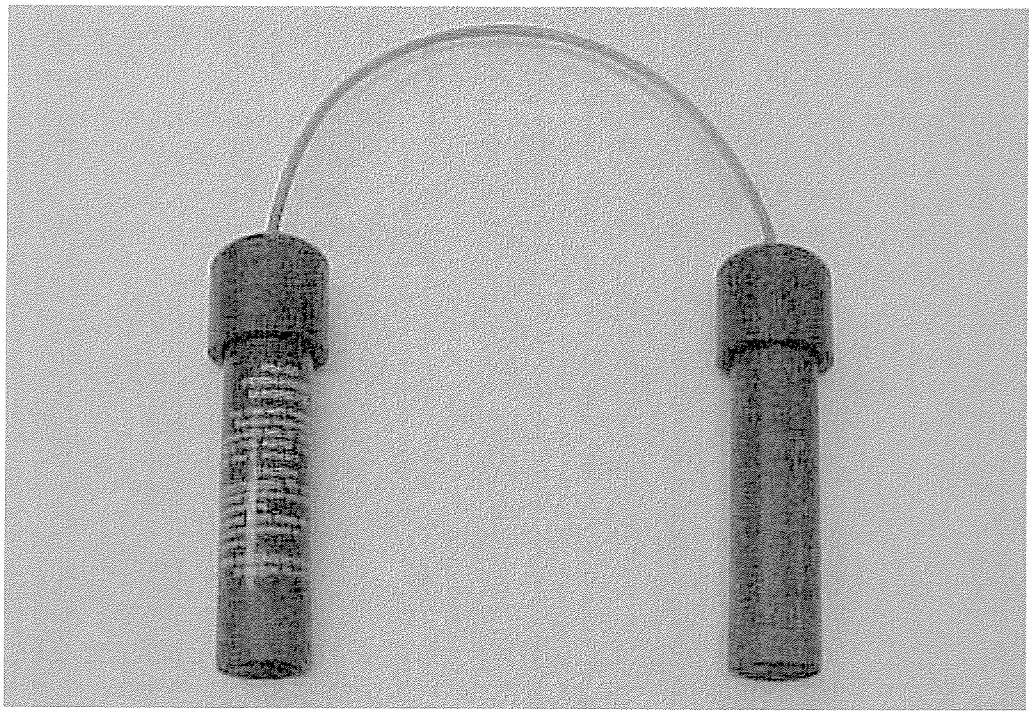


FIGURE 5-30 Permanent magnets.

Black Lights

The use of fluorescent particles requires a black light (see Figure 5-31). One type of blacklight contains a regulated current ballast transformer to limit the current drawn by the arc in the mercury vapor bulb. The light produced may also contain some white light and harmful UV radiation. It is therefore essential that a correct black light filter be used. This filter will allow the relatively harmless portion of the ultraviolet spectrum to pass through with a center wavelength of 365 nanometers (nm). The condition of the filter must be regularly checked to ensure that white light or harmful UV is not present.

Flux Direction Indicators

Flux direction can be determined by using one of several different indicators, as detailed below.

Pie Gauge

This is one of the most commonly used devices in MT. It consists of eight low-carbon steel segments, furnace brazed together, to form an octagonal flat plate that is then copper plated on one side to hide the joint lines. The gauge is placed on the test specimen during magnetization, with its copper face up. The particles are applied to this face and the orientation of the resultant field is displayed by the indications produced at the joint lines (see Figure 5-32).

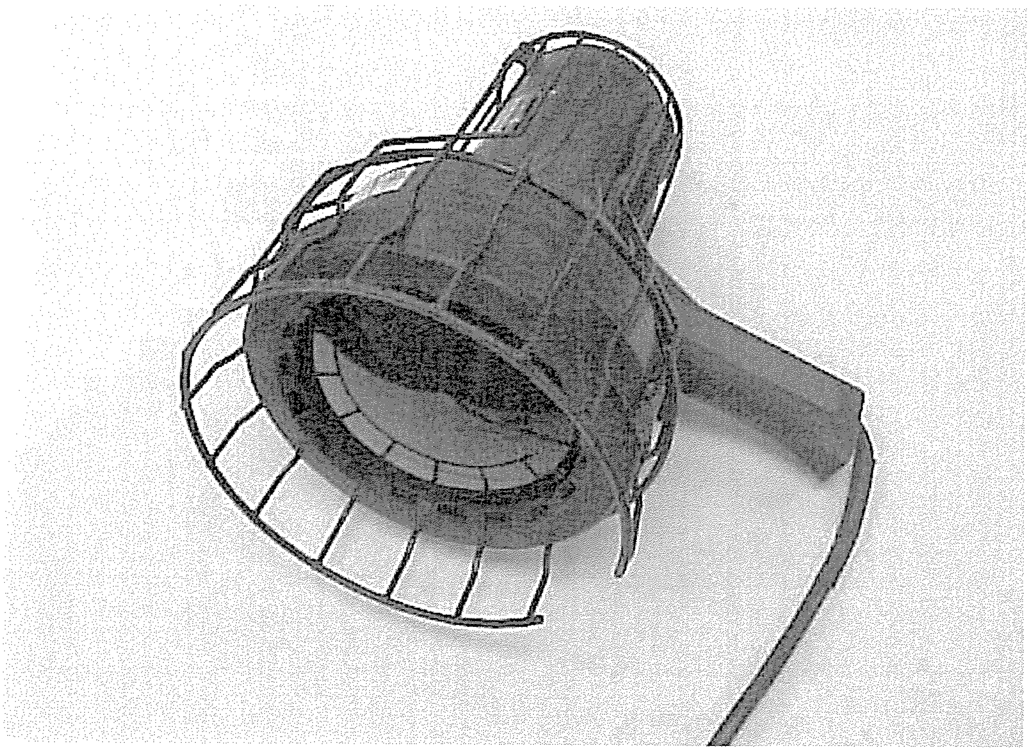


FIGURE 5-31 Black light.

Burmah Castrol Strips
These strips consist of a sandwich structure made up of a thin ferromagnetic foil with three fine slots running lengthwise sandwiched between two nonferromagnetic foils that conceal the slots. This is used in the same manner as the pie gauge. The slots in the strips will indicate the orientation of the flux lines (see Figure 5-33).

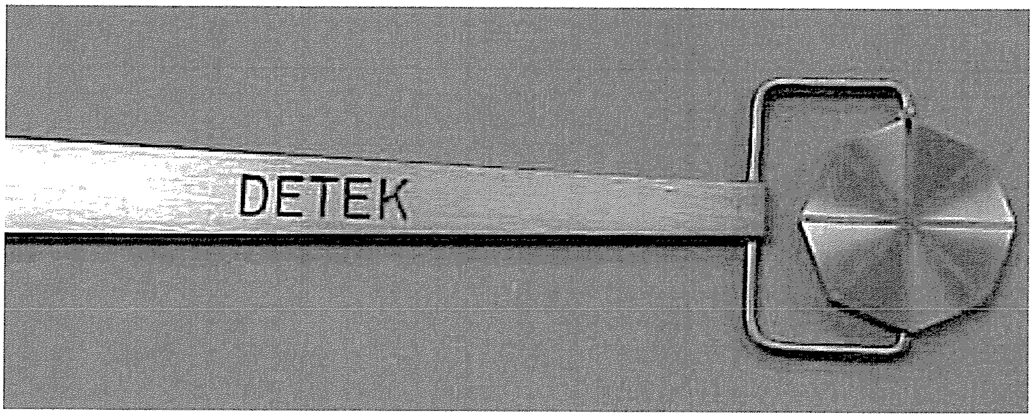


FIGURE 5-32 Pie gauge.

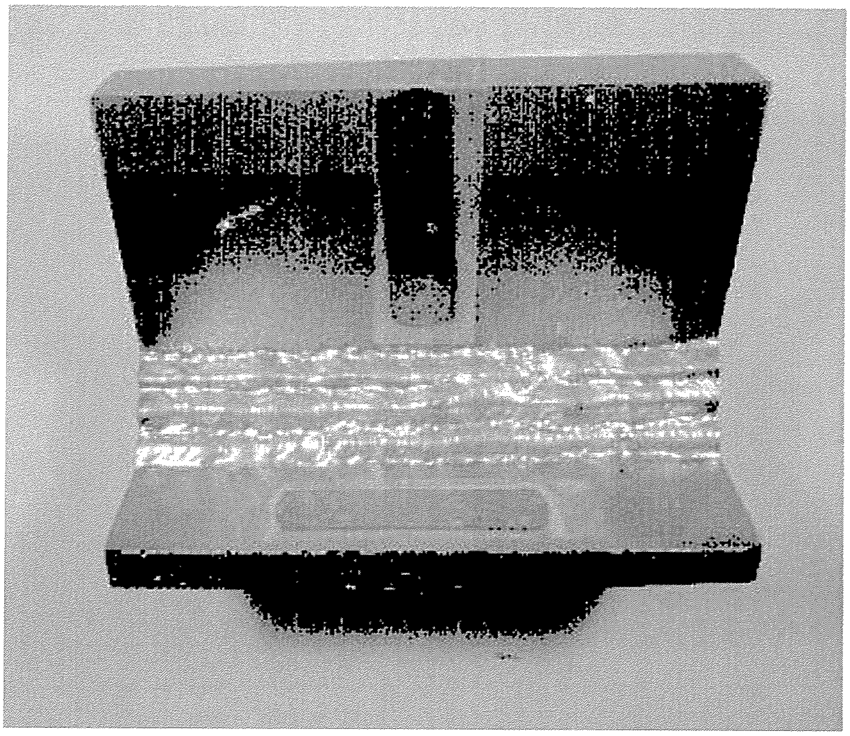


FIGURE 5-33 Burmah castrol strip.

Quantitative Quality Indicator (QQI)
This is a recent development of the foil concept and consists of a thin metallic foil, but instead of having slots in only one direction, the slots form circles or crosses, thereby making them able to indicate flux line direction without repositioning the indicators. The portion of the circle or the leg(s) of a cross determine which flaw orientation should be detected (see Figure 5-34).

AC Demagnetizing Coils

Separate coils are used when the demagnetization cannot be accomplished on the MT equipment. Many portable and mobile units have provisions for stepped reduction in current. The demagnetizing coil is often operated at a fixed current value and the reduction in field strength is achieved by passing the part(s) through the coil and beyond the coil along the central axis for a distance typically two to three times the length of the part(s).

This is effective for removing most of the residual fields because the residual vector of each cycle rapidly swings around to longitudinal. Thereafter, as the distance between the coil and the part increases, the field reduces until it is close to zero.

IV. TECHNIQUES

Magnetic particle testing techniques can be categorized into several key groups. They are:

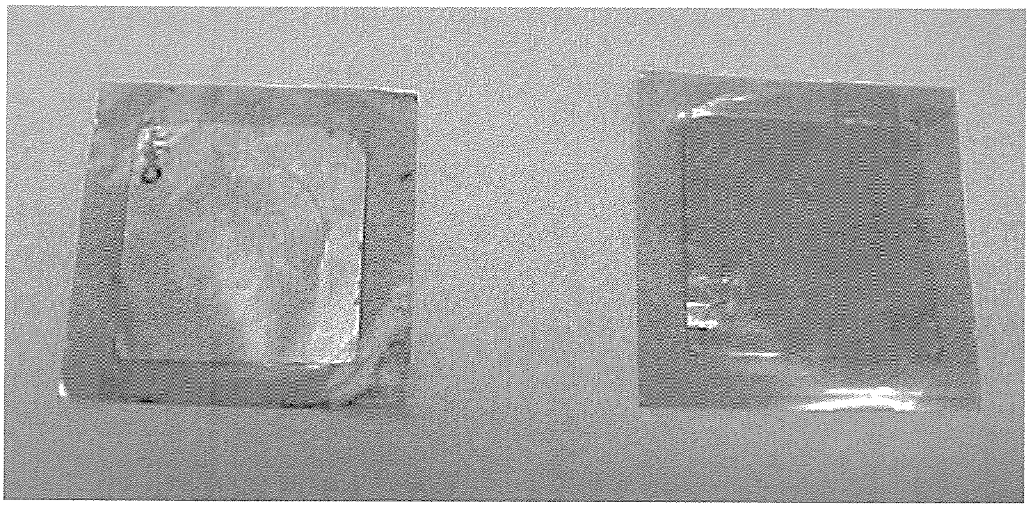


FIGURE 5-34 Quantitative quality indicators.

1. Method of magnetization
2. Continuous or residual
3. Particle types

Magnetization Techniques

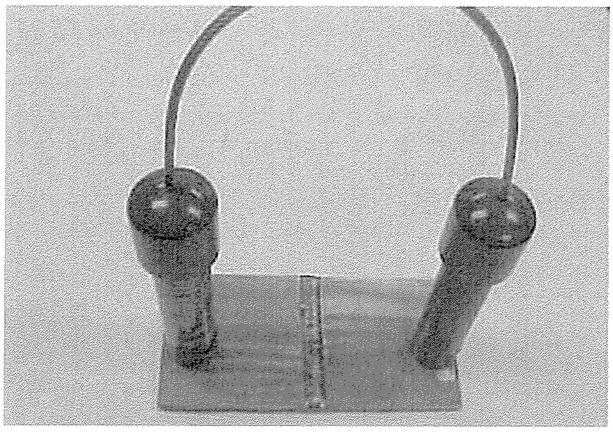
There are several factors that will dictate which magnetization technique is chosen for a particular test. The primary factor is the probable direction of anticipated discontinuities. The direction can usually be determined for fatigue cracks by studying the component loading and stress points, but in most other cases, the direction can be entirely unpredictable. Whether the direction is known or not, the component must inspected using two field directions perpendicular to one another, as discussed in Section II. This can be achieved using one or more of the magnetizing techniques described here.

The next factor in order of importance is the strength of the field to be applied, which will be discussed in Section V, Variables. The remaining factors to be considered include the end use of the part, the location of the part (in a factory, at a remote site, or in situ in a structure), and the susceptibility of the part to cracking due to heating or arc burns.

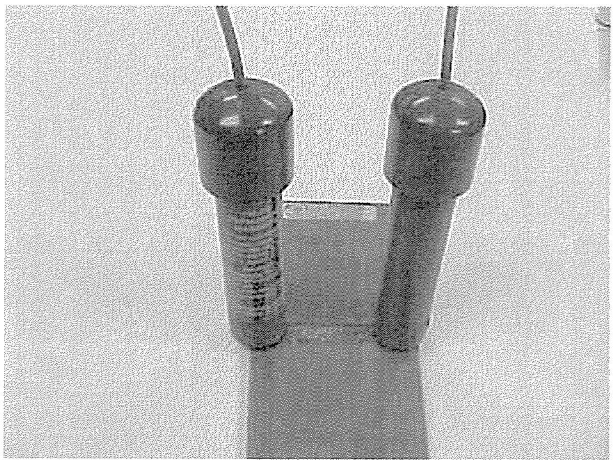
Magnetic Flow Techniques (Indirect)

The "indirect" or magnetic flow technique is defined as one in which the test part becomes part of the magnetic circuit by bridging the path between the poles of a permanent magnet or electromagnet. Figure 5-35(a) illustrates permanent magnets used in this way. The magnets can be turned 90°, as shown in Figure 5-35(b).

The AC yoke is an example of an electromagnet that is used in much the same way. They can also be used as magnetic flow devices, as shown in Figures 5-36(a) and 5-36(b). The main advantage of the indirect technique is that the risk of arc burning of critical components does not exist. Also, the use of permanent magnets or yokes can be very convenient for in-situ inspections in confined spaces or remote locations.



(a)



(b)

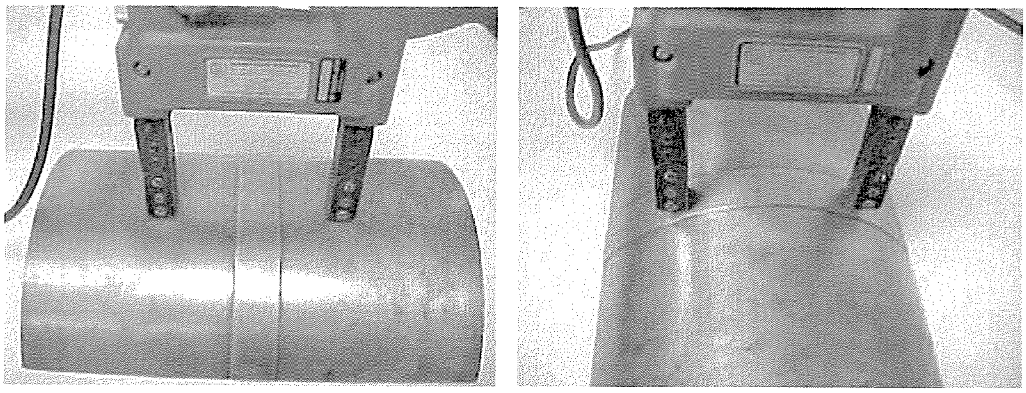
FIGURE 5-35 (a) Magnetic flow technique. (b) Magnetic flow technique at 90°.

Current Flow Techniques (Direct)

The "direct" technique is defined as one in which the magnetizing current flows through the part, thereby completing the electrical circuit. This is accomplished by placing the part between the "heads" of a stationary unit such as the one shown in Figure 5-25 or by using "prods," as shown in Figure 5-28.

The magnetic field formed with the direct technique is at right angles to the current direction of the current. In the case of a round bar held between the heads in a wet horizontal unit, the magnetic lines of force circulate around the bar as the current flows from one end to the other. This technique produces "circular magnetism." The flux line pattern in a flat plate when prods are used is illustrated in Figure 5-37.

One of the dangers in using the direct technique is that contact head or prod can cause a burn in the part if the high current is passing through a small contact area. For this reason, the contact faces on the heads should be flexible, and the tips of the prods should have a low melting point in order to spread the thermal load.



(a) (b)

FIGURE 5-36 (a) Electromagnet. (b) Electromagnet at 90°.

Coil Technique

Figure 5-38 shows a cylindrical component inserted into the windings of a coil. This produces longitudinal magnetism in the part as the current flows through the coil and creates a longitudinal field through and around the coil. This is referred to as the "longitudinal magnetization" technique. It has the advantage of not causing thermal damage, since a current does not pass through the part (indirect). In wet horizontal units, it is usual to have a fixed coil, usually containing five turns; but with mobile and portable units, it is more usual to wrap the current-carrying cable around the part to form a coil.

Central Conductor Technique

"Central" conductor is sometimes a misnomer because the opening through which the nonmagnetic conductor is positioned is not always central. The technique is sometimes referred to as the "threader bar" technique to show the distinction. Figure 5-39 is a sketch of a tubular component being tested using this technique. Like the coil technique, it is also indirect because the current passes through the conductor and not the part. This technique produces circular magnetization and can be used to inspect the insider and outside surfaces of the part.

Continuous and Residual Techniques

There are four techniques that can be used to inspect parts using these methods of magnetization, they are:

1. Dry continuous
2. Dry residual
3. Wet continuous
4. Wet residual

There are advantages and limitations associated with each technique and careful selection must be made depending upon the application. The term "continuous" is used when the

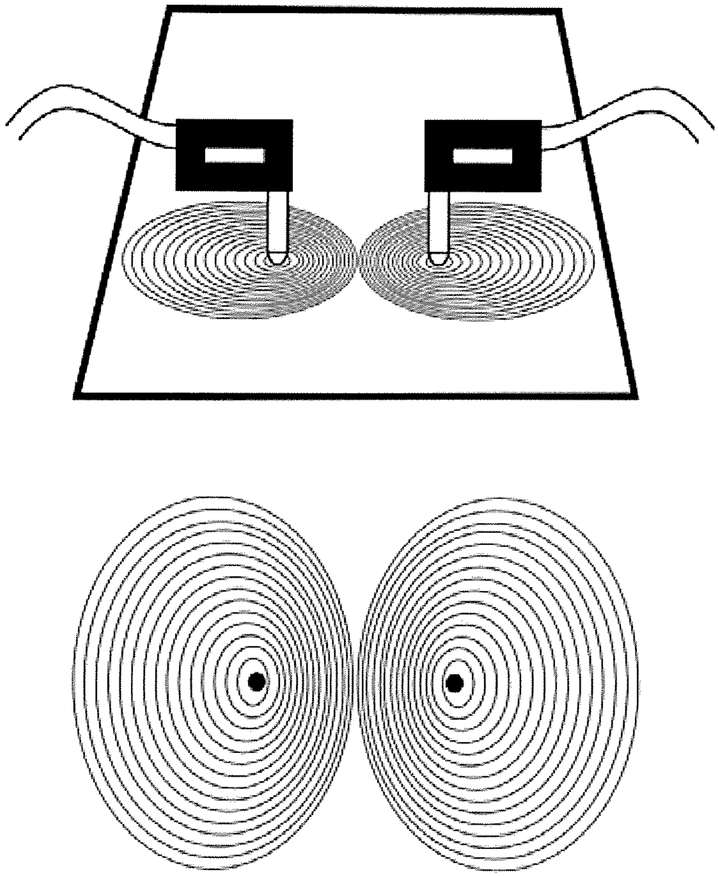


FIGURE 5-37 Sketch of flux lines—DC prod.

magnetic particles are applied while the current is still flowing. "Residual" is used when the material has sufficient retentivity to allow application of the magnetic particles after the current has ceased. "Dry" means that the magnetic particles are applied in fine particle form. "Wet" means that the particles are applied suspended in a liquid carrier. The particles may be suspended in kerosene or other similar petroleum distillates or may be suspended in water containing specially formulated additives. A brief description of the key parameters of each technique follows.

Dry Continuous

This technique uses dry particles that are applied while the magnetizing force is on. The particle application must cease before the current flow ceases. The use of dry particles is useful for detecting slightly subsurface discontinuities, since the particles have higher permeability compared to the particles in a wet suspension. This higher permeability is needed to detect the weaker leakage fields produced by slightly subsurface discontinuities. Applying the particles during the magnetization provides maximum sensitivity, since the flux density will always be at its maximum during the current flow.

One disadvantage of dry particles is their relatively poor mobility when used with DC current. Mobility can be improved by gently tapping the test part or by using half-wave rectified or AC current. The pulsed nature of the half-wave rectified and AC current creates a vibratory effect on the particles, causing them to "dance" toward the leak-

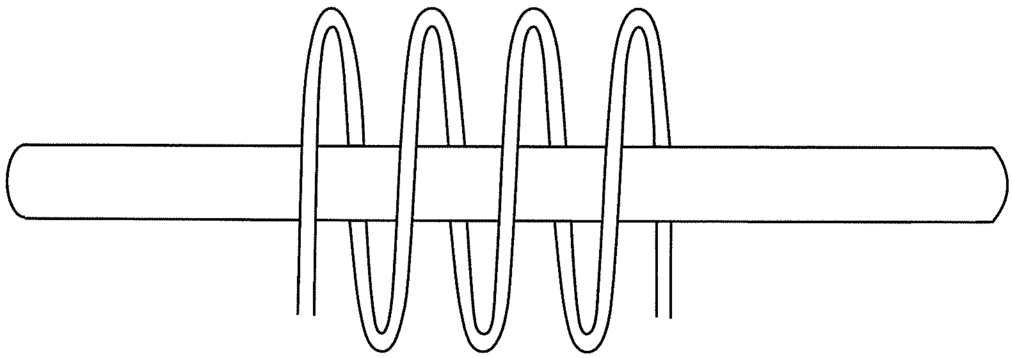


FIGURE 5-38 Coil technique.

age fields. This technique is used extensively for field inspections using prods or yokes. Care must be exercised when removing the excess particles from the test surface to minimize any effect on the particles held by discontinuities. In this respect, the current should also be flowing while the excess particles are being removed with low air pressure.

Dry Residual

This technique also uses dry particles, but differs from the previous technique in that the magnetizing current is applied for a brief period, which produces a residual magnetic field in the part (DC is preferred). The dry particles are applied after the magnetizing force has ceased. The retentivity of the material produces a residual magnetic field, which results in leakage fields at discontinuities open to the surface. This technique is suitable only with materials having high retentivity. This must be determined prior to selecting this technique.

There are further disadvantages when compared to the continuous techniques. The leakage fields produced will be weaker, thereby reducing the sensitivity. Small and subsurface discontinuities are difficult to detect. The lack of the magnetizing current's vibratory effect during particle application will also reduce sensitivity due to the decrease in particle mobility.

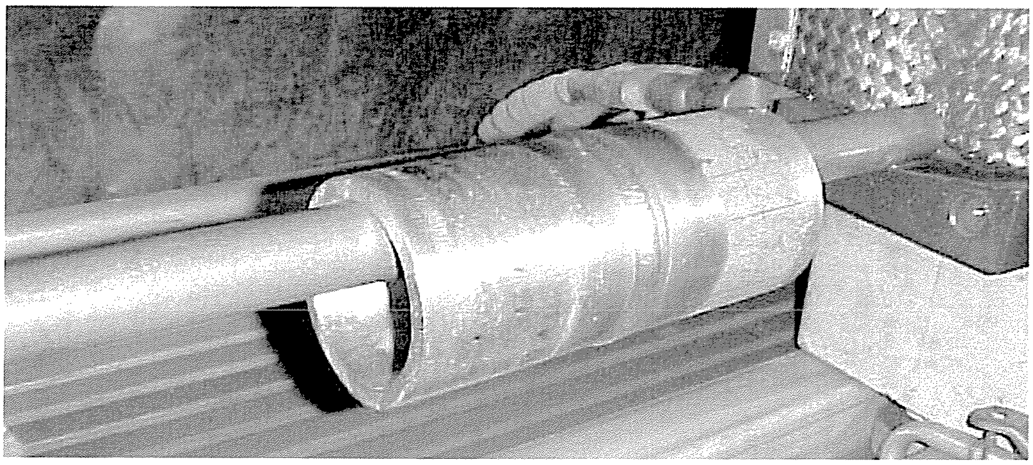


FIGURE 5-39 Central conductor/threader bar.

The main advantage of this technique is that multiple parts or batches can be magnetized simultaneously, then examined individually after particle applications. This technique would only be used when a lower sensitivity of high-retentivity parts is acceptable.

Wet Continuous
This technique uses particles suspended in a liquid carrier and is applied simultaneously with the magnetizing current. Compared to the dry particles, the suspended particles are generally of a lower permeability, which makes this technique less favorable for the detection of slightly subsurface discontinuities.

There are advantages and limitations of the different liquid carriers. Kerosene and petroleum distillates are more expensive and may produce some health and flammability problems, but they also help to lubricate the sliding mechanisms on the wet horizontal unit and do not constitute a corrosion source for the equipment or the parts being inspected. Water, on the other hand, is inexpensive, readily available, poses no health or flammability hazards, but is a source of corrosion. Using corrosion-inhibiting additives can reduce the corrosion risk, although it can never be completely eliminated.

The greatly improved mobility of the particles makes this technique very suitable for the detection of small surface discontinuities. Additionally, the suspension will adhere to complex shapes better than dry particles, due to the surface tension combating the effects of gravity. These advantages combined with the high flux densities of the continuous technique provide the maximum sensitivity for surface discontinuities. When using this technique, the suspension flow should cease before the current stops, otherwise indications may be washed away.

Wet Residual
This technique also uses suspended particles, but the suspension is applied after the magnetizing force has been stopped. As previously detailed, the residual method will be of a lower sensitivity than the continuous method, but has the advantage of increased inspection speed, due to multiple part or batch inspection possibilities.

Color and Fluorescence
Each of the above techniques may be further subdivided into color contrast or fluorescent particles techniques depending on the availability of equipment and materials, type of discontinuity, and sensitivity requirements. Some inspection requirements will mandate the use of fluorescent particles, due to the increased sensitivity provided by the higher contrast ratio.

Summary of Technique Choices

It is obvious that there are many options and choices to consider when developing the most suitable technique for the part to be inspected. In order to provide the optimum inspection approach, some of the key areas to be evaluated include:

- Material type
- Part configuration
- Dimensions
- Surface condition
- Type and location of discontinuities anticipated
- Code and specification requirements
- Customer-specific requirements

Once these are known, the choice of technique can be made. These key items should be considered:

- Type of current (AC, HWDC, FWDC)
- Wet suspension or dry particles
- Visible or fluorescent particles
- Direct or indirect magnetization
- Continuous or residual
- Stationary or portable equipment

The best combination can be determined through qualification by validation through the use of controlled test specimens.

Quality Control Considerations

In order to maintain consistency and high level of control over the MT process, it is highly recommended (and in many cases required) that certain checks be completed on the system. Probably the best ongoing quality check is to periodically inspect a controlled test specimen with known discontinuities. The test specimens should be carefully maintained and the periodic checks recorded.

A suspension concentration test, sometimes referred to as a "settling test," should be performed daily. This test is usually performed with a 100 mL ASTM pear-shaped centrifuge tube (see Figure 5-40. A sample of the suspension (after thorough agitation) is deposited directly into the tube from the hose dispenser and allowed to settle, typically for a period of 30 minutes. To assist in the settlement, the tube may be "run" through the demagnetizer. The purpose of this check is to assure that the proper concentration of particles is being maintained in the liquid carrier. The applicable specifications will detail the concentration range. Typical ranges are:

- For visible particles, 1.0 to 2.4 mL/100 mL
- For fluorescent particles, 0.1 to 0.4 mL/100 mL

A settling test tube in a stand is illustrated in Figure 5-40.

The Ketos ring seen in Figure 5-41 is a device made of tool steel and is designed to show the effectiveness of the MT field and the relative penetration based on the number of holes that display indications. Both wet suspension and dry particles are used, and general practice calls for the following:

	Number of Hole Indications	
Amperage (FWDC)	Wet Suspension	Dry Particles
1400	3	4
2500	5	6
3400	6	7

As with all the quality checks, it is essential that results of the ring test be recorded.

A final check for the presence of residual magnetism should always be made using a simple field indicator.

Other QC checks may include:

- Suspension contamination
- Ammeter accuracy

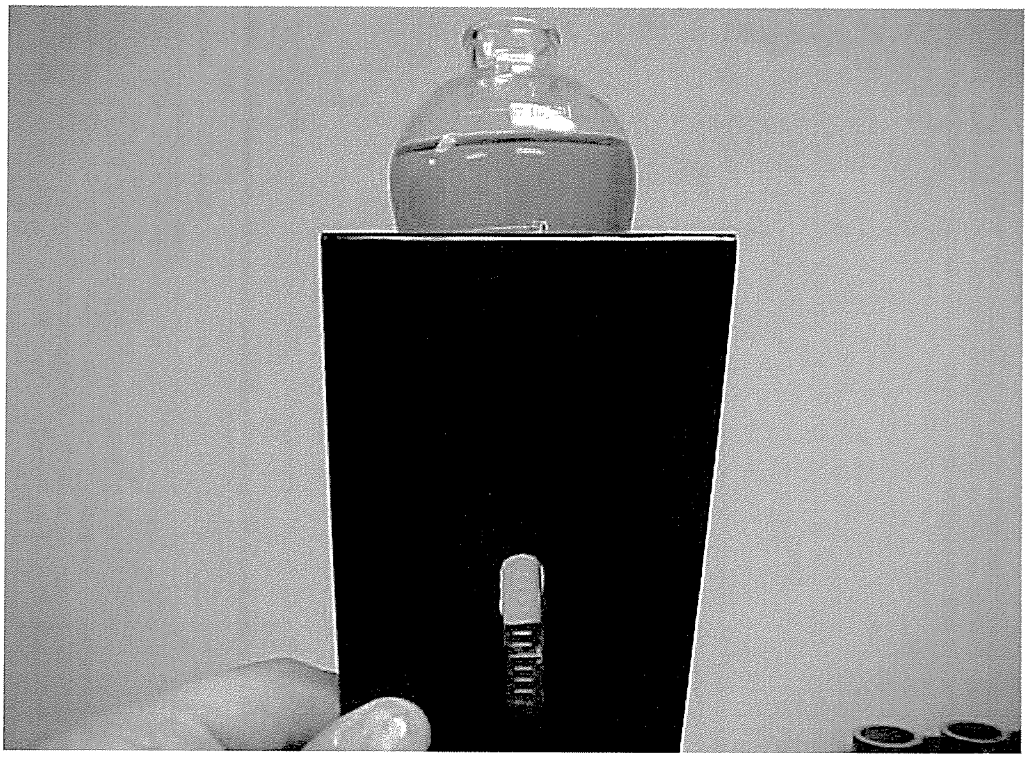


FIGURE 5-40 Settling test.

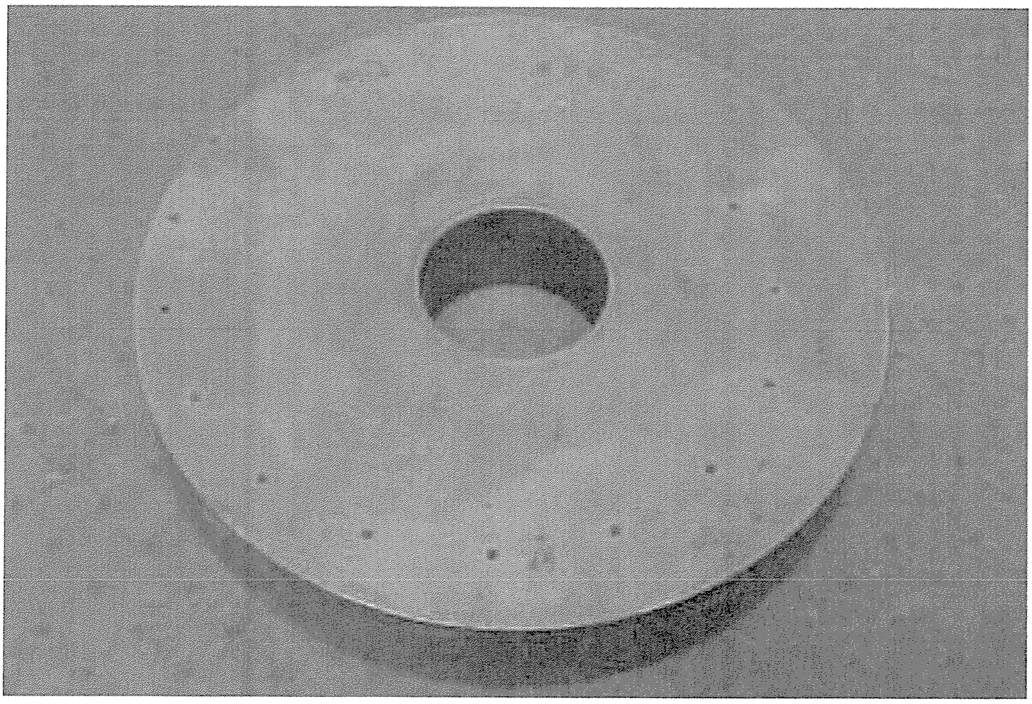


FIGURE 5-41 Ketos ring.

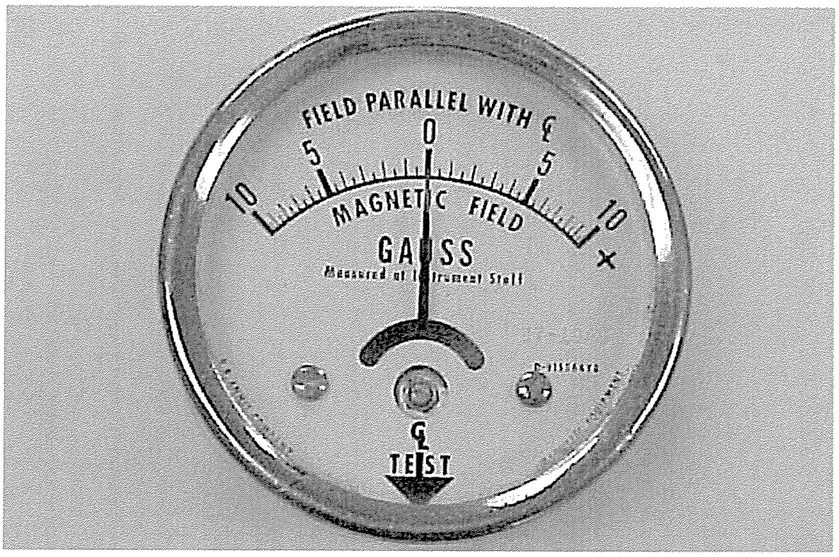


FIGURE 5-42 Field indicator.

- Timer performance
- Black light intensity
- White light intensity
- Ambient visible light
- Water in oil-based suspension liquid
- Fluorescent particle brilliance

The key to successful MT and control of the system is to periodically perform the appropriate checks and maintain a detailed record of them in a logbook.

V. VARIABLES

As mentioned in previous sections, there are many variables to consider when deciding upon the best inspection technique for a particular application. A listing of some of the considerations and options follows.

Considerations

Customer requirements—specifications, standards, or drawing requirements
Equipment availability—AC/DC, stationary, portable, black light, etc.
AC power availability—needed for all except permanent yokes or magnets
Part size requirements—e.g., will it fit into a wet horizontal unit?
Part location—will it require portable equipment?
Types of discontinuities anticipated—orientation and location
Retentivity of test material—must be high if residual technique is to be used

Options

AC or DC (HWDC or FWDC) Magnetizing Current
Use AC for surface discontinuities or those that would be expected during in-service inspection. Use DC for deeper penetration and possible detection of slightly subsurface discontinuities.

Continuous or Residual
Use the residual technique for inspection of highly retentive materials, especially where large batches are to be inspected. Use the continuous technique for all other applications, especially where higher sensitivity is required.

Wet or Dry Particle Application
Wet particles have better mobility, but generally lower permeability. Use wet for small surface discontinuities or service-induced discontinuities. Use dry for slightly subsurface discontinuity detection.

Color Contrast or Fluorescent Particles
Color contrast does not require a darkened viewing area or black light illumination, however, the sensitivity will be lower than that of fluorescent particles. Use color contrast for field inspections where highest sensitivity is not required. Use fluorescent where maximum sensitivity is essential.

Stationary, Mobile, or Portable Units
In a production or maintenance facility, the versatility of the wet horizontal unit makes it the ideal choice; however, many applications involving immovable or large test objects eliminate this possibility, resulting in the need for mobile or portable units.

Amperage to be Used
Will be determined based on specification and standard requirements and the test part dimensions.

Amperage Selection

Many international standards give tables of current values based on the type of current available in the magnetizing equipment, the sensitivity required, and the component geometry and material. In the absence of a specified standard, the following general "rules of thumb" have been widely used.

For direct circular magnetization of basically round sections use a range of 300–800 amps per inch diameter (12–32 amps/mm). This is usually 500 amps per inch (20 amps/mm) based on peak value for full-wave rectified current. Values above 500 amps/inch diameter (20 amps/mm) are only recommended for low-permeability materials or for slightly subsurface discontinuity detection.

Example 1. For a 1.5″ diameter bar, 9″ long, 1.5″ × 500 amps per inch = 750 amps.

For central conductor circular magnetization of hollow round components with **conductor bar placed concentrically** with the component, the same current values stated above would apply, based on the outer diameter or inner diameter, depending on which surface is to be examined.

Example 2: Tubular component, 2″ outside diameter, 1.5″ inside diameter, using a 1″ diameter central conductor (looking for OD discontinuities), 2″ outside diameter × 500 amps per inch = 1000 amps.

For central conductor circular magnetization of hollow round parts, with the conductor bar placed against the inner surface of the component the same formula should be used for calculating the direct current amperage. However, instead of basing the calculation on the outer diameter, it should be based on the diameter of the central conductor plus two times the wall thickness of the part. The area that is considered to be effectively magnetized using this technique is a distance around the inner diameter equating to four times the central conductor diameter. The part should be rotated and reinspected as often as necessary to achieve a minimum of a 10% overlap between each examination area.

Example 3: Outside diameter 2″, inside diameter 1.5″, 1″ diameter central conductor, wall thickness 0.25″:

Central conductor = 1.0″

2 × wall thickness; 2 × 0.25″ = 0.5″

Part diameter = 1.5″

Part diameter × 500 amps per inch = 1.5″ × 500 amps per inch = 750 amps

For longitudinal magnetization using a rigid coil, when the part cross sectional area (cross sectional area is found by squaring the radius and multiplying by π) is **less than one tenth (10%) of the coil inner cross sectional area (low fill factor coil),** the number of "ampere turns" to be used can be found using one of the following formulas:

If part is placed against inside of coil, ampere turns
= 45,000 ÷ (part length) × (part diameter)

If part is placed centrally in the coil, ampere turns
= 43,000 × coil inner radius (6 × length/diameter ratio) – 5

Note 1. The length-to-diameter ratio must be in the range 2 (minimum) to 15 (maximum). Parts shorter than twice the diameter should not be inspected using the coil technique. Parts with a length greater than 15 times the diameter should be tested using a number of "shots" until the entire length is covered.

Note 2. The "ampere turns" value must then be divided by the number of turns in the coil to determine the amperage to be used.

Example 4. Inspecting a 1.5″ diameter round bar with a total length of 9″ using a five-turn coil with an internal diameter of 12 inches. Determine if the coil is a low fill factor by comparing area ratios:

Area of part = 0.75″ (radius) squared × π = 1.767 square inches

Area of coil = 6″ (radius) squared × π = 113 square inches

Ratio of areas = 1.767 divided by 113 = 1.56% (low fill factor)

Amperes to be used if the part positioned the side of coil:

$$= 45{,}000 \div \frac{9}{1.5}$$

$$= 45{,}000 \div 6$$

$$= 7500 \text{ ampere turns}$$

$$\text{Divide by 5 turns} = \frac{7500}{5} = 1500 \text{ amps}$$

Amperes to be used if the part is positioned centrally in coil:

$$= \frac{(\ 43{,}000 \times \text{coil radius}\ )}{[6 \times (\text{length/diameter ratio})]} - 5$$

$$= \frac{(43{,}000 \times 6\,)}{(6 \times 9''/1.5'') - 5}$$

$$= \frac{(258{,}000)}{(6 \times 6) - 5}$$

$$= \frac{(258{,}000)}{(36) - 5}$$

$$= \frac{258{,}000}{31}$$

= 8322 ampere turns

$$\text{Divide by 5 turns} = \frac{8322}{5} = 1664 \text{ amps}$$

For longitudinal magnetization using a coil (either rigid or wrapped cable), where the cross-sectional area of the part is at least one-half (50%) of the coil inner cross-sectional area (high fill factor coils), the number of amperes to be used can be calculated by using the following formula:

$$\text{Ampere turns} = 35{,}000 \div \frac{(\text{part length})}{(\text{part diameter})} + 2$$

Again, the actual amperage setting is determined by dividing the "ampere turn" value by the number of turns.

Example 5. Inspecting a 1.5″ diameter round bar with a total length of 9″ using a five turn coil with an internal diameter of 2″. The fill factor is determined by dividing the coil area by the part area:

Area of coil = 1″ (radius) squared × π = 3.142″

Area of part = 0.75″ (radius) squared × π = 1.767″

Ratio of areas = 1.767 divided by 3.142 × 100 = 56.23% (high fill factor coil)

$$\text{Ampere turns} = 35{,}000 \div \frac{(9)}{(1.5)} + 2$$

$$= 35{,}000 \div (6) + 2$$

$$= 35{,}000 \div 8$$

= 4375 ampere turns

$$\text{Divide by five turns} = \frac{4375}{5} = 875 \text{ amps}$$

For longitudinal magnetization using a coil where the part cross sectional area is between one tenth (10%) and one half (50%) of the coil inner cross sectional area (intermediate fill factor coils), the number of Amperes can be calculated by using the formula:

Ampere turns = [(Ampere turn value for high fill factor coil) × 10 – (coil cross-sectional area/part cross-sectional area) ÷ (8)] + [(ampere turn value for low fill factor coil) × (coil cross-sectional area/part cross-sectional area – 2)] ÷ 8

Example 6. Inspecting a 1.5″ diameter round bar with a total length of 9″ using a five turn coil with an inside diameter of 4″, the fill factor ratio is determined by dividing the coil inner diameter by the part outer diameter:

Area of the coil = 2″ (radius) squared × π = 12.566 square inches

Area of the part = 0.75″ (radius) squared × π = 1.767 square inches

Ratio = 1.767 divided by 12.566 × 100 = 14.06% (intermediate fill factor coil)

From Example 5 (high fill factor coil), amperage for this part would be 875 amps. From Example 4 (low fill factor coil) ampere turns for this part would be 1500 amps. Insert the above values into the formula to give

$$875 \times \frac{(10 - 7.11)}{8} + \frac{1500 \times (7.11 - 2)}{8} = \frac{875 \times 2.89}{8} + \frac{1500 \times 5.11}{8}$$

$$\frac{2528.75}{8} + \frac{7665}{8} = 316 + 958 = 1274 \text{ amps}$$

Note: Amperages to be used are the calculated amperages ± 10%.

For circular magnetization using prods, the amperage to be used is usually determined by the prod spacing and part thickness. For part thicknesses up to $\frac{3}{4}$″ (19 mm), 90–115 amps per inch (3.5–4.5 amps per mm) of prod spacing should be used. For part thicknesses over $\frac{3}{4}$″ (19 mm), 100–125 amps per inch (4–5 amps per mm) of prod spacing should be used. The prod spacing will usually be between 2″ (50 mm) and 8″ (200 mm).

For longitudinal magnetization using a yoke. When using an AC yoke, the yoke should be proven to having a field strength capable of lifting a dead weight of at least 10 lbs (45 newtons) with a 2–4″ (50–100 mm) spacing between the legs.

When using a DC yoke or a permanent magnet, it should be proven to have sufficient lifting capability to lift a dead weight of 40 lbs (135 newtons) with a 2–4″ (50–100 mm) spacing between the legs. Alternatively, a weight of 50 lbs (25 newtons) with a leg spacing of 4–6″ (100–150 mm) spacing can be used. It should be noted that there may be different weight requirements depending upon the applicable code or specification.

Note: Some codes require that the leg spacing for the lift test be the same as to be used during inspection.

Caution!

Although the above formulas will produce exact values for required amperages, it should be mentioned that the correct amperage requirements vary based on the applicable specification. Some specifications take into account the variations in flux density due to the differences in permeability between the different steels and also consider the type of current used and the type of meter used to measure the current.

There are specifications that recommend the use of a hand-held gauss meter (such as in Figure 5-43) held against the part surface to determine if sufficient flux density is being generated in the part. This practice does not take into consideration the permeability variations within the part. A part with a high permeability will concentrate more of the flux within itself, producing the high-density flux necessary for acceptable sensitivity. The flux density in the air surrounding the part will be low as a result of this. A low reading will therefore be produced on the gauss meter. If the part were to be replaced with a part with lower permeability, the flux density within the part would not be as high and might

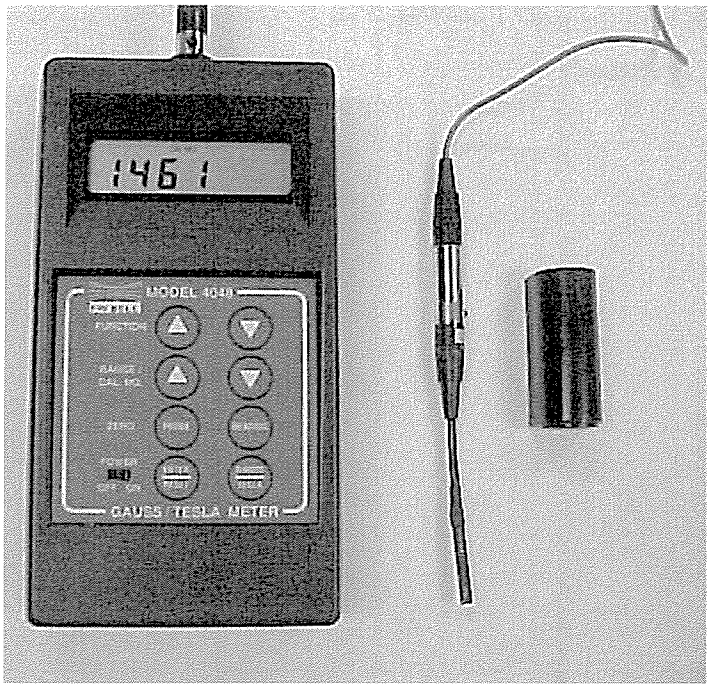


FIGURE 5-43 Hand-held gauss meter.

not be sufficient to produce reliable indications. However, the reading on the gauss meter would be higher due to the higher flux density in the air surrounding the part.

In summary, although code and specification requirements are very detailed, the practice of determining if sufficient flux is being generated is not an exact science. The ideal way to determine if sufficient flux is being generated in the part is to have an identical part with an actual discontinuity of the type, size, and location as those being sought. If this can be reliably found, then the probability of finding an identical or larger discontinuity in the test part is very high.

VI. EVALUATION OF TEST RESULTS AND REPORTING

The evaluation of test results is the most critical stage in the magnetic particle inspection process and greatly relies on the qualifications of the inspector. The ability of an inspector to observe an indication depends upon the correct application of the proper techniques, and using equipment and accessories that are functioning correctly. Another consideration is the inspector's ability to perform the test correctly. Competence should have previously been demonstrated by satisfying qualification requirements. The qualification process should also include a vision examination to prove visual acuity and ability to distinguish the colors associated with the MT technique to be used.

Classification of Indications

Once detected, the indications should be classified as either "false," "nonrelevant," or "relevant" before final evaluation.

False Indications

False indications can be produced by improper handling and do not relate to the part's condition or use. An example is "magnetic writing." This is typically produced by the formation of indications at local poles that are created when the part comes in contact with another magnetized part prior to or during inspection. This can be eliminated by demagnetization and repeating the inspection.

Magnetic writing is most likely to occur when using the residual method, through poor handling that allows the individual parts to touch. The continuous technique may require the demagnetization of parts before the next inspection to preclude the possibility of magnetized components touching. This type of false indication can be eliminated through careful handling.

Other sources of false indications may be caused through the use of excessively high magnetizing currents or inadequate precleaning of the parts to remove oil, grease, corrosion products, and other surface contaminants.

Nonrelevant Indications

These are the result of flux leakage due to geometrical or permeability changes in the part. Examples of geometric causes include splines, thread roots, gear teeth, keyways, or abrupt section changes (see Figure 5-16). A concern with these conditions is that they may also be stress risers and could be the origin for fatigue-induced cracks. These conditions are therefore some of the most critical; the possibility that one of these nonrelevant indications can conceal a crack must be considered. Other potential sources of nonrelevant indications include localized permeability changes in the part, which may be due to localized heat treatment or variations in hardness, and may also occur at the fusion zone of a weld.

Relevant Indications

These are produced by flux leakages due to discontinuities in the part. When these discontinuities are not in compliance with a code, they are classified as rejectable. If they meet the acceptance criteria they are considered to be acceptable discontinuities. Discontinuities that do not permit the part to be used for its original purpose or can potentially cause the part or fail are classified as defects.

Visual Appearance

Generally speaking, **surface** discontinuities will provide sharp distinct indications, which resemble very closely the shape and size of the discontinuity producing the leakage field (see Figure 5-44).

It is not feasible to describe every possible type of discontinuity and its appearance when using the MT method. However, a detailed description of discontinuities and their appearances and causes is contained in Chapter 2.

Subsurface discontinuities will produce weaker, diffuse, and broad indications, which become less well defined as their depth below the surface increases.

Depth Limitations

It is not possible to define at exactly what depth a discontinuity can be detected because of the many variables present. It has been claimed that subsurface discontinuities have been detected as deep as 0.240″ (6 mm) from the surface.

Sensitivity varies greatly with depth below the surface. A surface crack will usually be easily detected providing the correct current and flux line direction are employed. It is

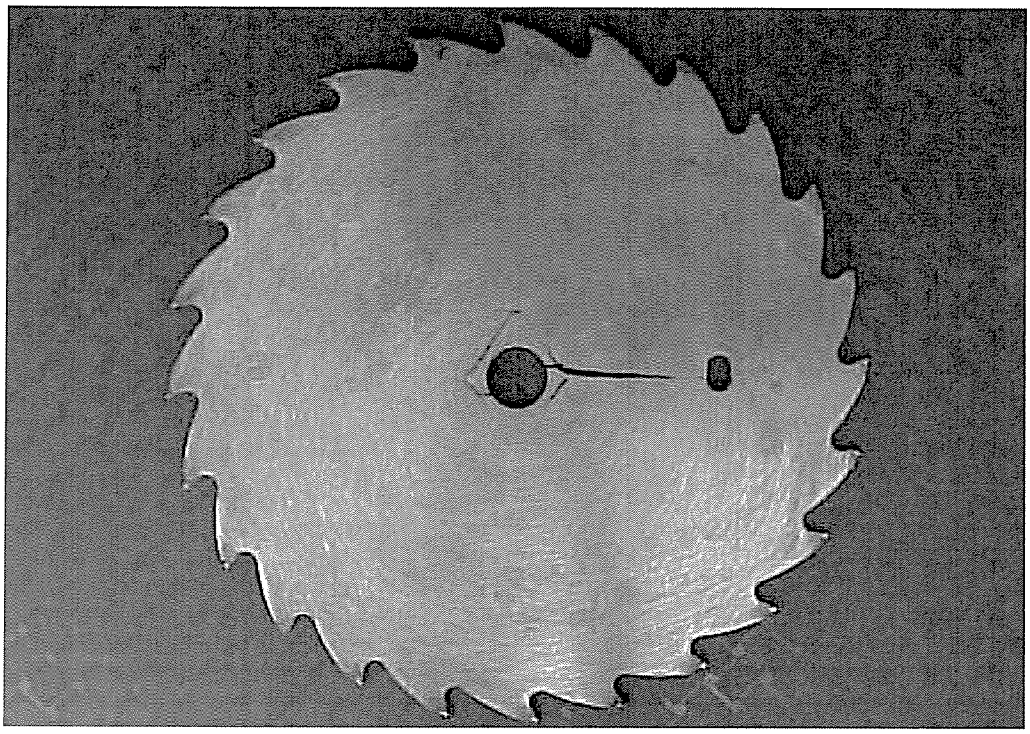


FIGURE 5-44 Indication of a quench crack in a saw blade.

reasonable to expect reliable detection of cracks on the order of at least 0.040″ or (1 mm) in length.

Reporting

When the parts have been inspected and all indications evaluated, it will be necessary to prepare a report detailing the results of the test and, if applicable, the size, location, and orientation of discontinuities found. This report may vary considerably from company to company, but as a minimum, it should meet customer requirements and should typically include the following data:

1. Contract and customer
2. Inspection company
3. Date of inspection
4. Inspector's name and qualification and certification level
5. Report number or identification
6. Applicable codes, specifications, or procedures, including type and technique of inspection
7. Acceptance criteria
8. Component description, part number, and serial number

9. Flux line direction with respect to discontinuity orientation
10. Other identification details as requested in the contract; for example, batch or order number.
11. Material batch number (particles, liquid carrier, etc.)
12. Results of inspection, including recording of indications as detailed below
13. Signature or inspection stamp of inspector

A detailed, concise report will enable future evaluations by other inspectors. There are several ways of achieving this:

1. A descriptive written report including significant dimensions and indication location can be complied.
2. A photograph may be taken under the correct viewing conditions. Black light illumination in a darkened environment works fine if the correct exposure (usually several seconds) is used and a camera is mounted on a tripod. It may be necessary to vary the exposure time several times to ensure that the best lighting and exposure parameters are met.
3. A free-hand sketch may be used to supplement the data. Again, key dimensions must be included. Unfortunately, not everyone is a good artist, and the quality and usefulness of sketches can be questionable.
4. A piece of transparent tape may be used to lift the indication from the test surface if using dry particles. When peeled off, the tape will retain the shape and size of the indication through the adherence of the particles to its adhesive layer. The tape can then be applied to the report or other suitable background material to render the indication more visible.
5. Aerosol-based, strippable lacquer may be applied in several thin layers, allowing each layer to dry before applying the next, until sufficient thickness exists, allowing the solidified, flexible film to be peeled off the part.
6. Magnetic rubber inspection may be used to create a permanent record of indications. Magnetic rubber inspection involves using a two-part liquid rubber kit consisting of:
   a) Room temperature vulcanizing (RVT) rubber supplied in a liquid form. This liquid rubber also contains ferromagnetic powder.
   b) A catalyst, which when mixed will cause the mixture to solidify at a controlled rate.

   When mixed together, the rubber solution is poured onto the area of inspection and a magnetizing force applied during the "cure" time. The cure rate should be slow enough to allow the ferromagnetic powder to migrate to the flux leakage fields, but not so slow as to delay the inspection longer than necessary. Magnetic rubber materials with curing ranges from 5 minutes to 4 hours are available. When the rubber is solidified, it can be peeled off and the indications created by the flux leakage can be observed and retained as a record.

   The magnetic rubber inspection technique has uses beyond recording indications. It can also be used to inspect areas and surfaces that are inaccessible for standard MT inspection, such as inside blind fastener holes, particularly threaded holes. The rubber can be poured into the hole and a permanent magnet applied across the hole during the cure. After solidification of the rubber, the solid (but, flexible) rubber plug is removed from the hole and the indications from within the hole can be viewed on the outer surface of the plug. A small stick or other device can be cast into the plug to facilitate easy removal.

VII. APPLICATIONS

The magnetic particle test method is effective for the detection of surface and slightly subsurface discontinuities in ferromagnetic parts. It can be used as an inspection tool at all stages in the manufacture and end use of a product.

Stages of a Product's Life Cycle

Discontinuities can occur in any of the following stages of the product's life cycle and ican be classified accordingly.

Inherent

As the metal cools and solidifies to produce the original ingot, numerous discontinuities can be introduced. Inherent discontinuities that can be detected by magnetic particle testing include nonmetallic inclusions (sometimes referred to as stringers") and seams located at the surface.

Primary Processing

When the original material has become solid, it must be worked and formed to produce a rough shaped product. During these processes, the part is said to be in its "primary processing stage." Typical primary processes include, forging, casting, rolling (hot and cold), extrusion, and drawing. During these processing operations, discontinuities may be produced or existing discontinuities may be modified. Examples of primary processing discontinuities detectable by magnetic particle testing include:

- Forging bursts
- Forging laps
- Rolling laps, seams, and stringers
- Rolling seams
- Laminations (at the edges of plates and sheets)
- Casting shrinkage (at the surface)
- Casting inclusions (at the surface)
- Casting cold shuts (at the surface)
- Casting hot tears (at the surface)

Secondary Processing

After rough shaping the metal in the primary processing stage, it is further refined and shaped to produce finished products. This stage is referred to as "secondary processing" and can include such processes as machining, grinding, plating, and heat treatment. These secondary processes may also produce discontinuities or change the appearance of existing ones. Examples of secondary processing discontinuities detectable by magnetic particle testing include:

- Quench and heat cracks
- Grinding cracks (or checks)
- Machining tears
- Plating cracks

Welding

When parts are joined together by a welding process, numerous discontinuities may be created. Examples of the welding processes are found in Chapter 2. The following is a list of welding related discontinuities that may be detected by magnetic particle testing when at or close to the surface.

- Cracks (longitudinal, transverse, and crater)
- Lack of fusion
- Incomplete penetration (if accessible)
- Entrapped slag
- Inclusions
- Overlap or "cold" lap

Service

When the part is put into service and subjected to stresses and environments that may be detrimental to its structure, service discontinuities may result. Those that are detectable by magnetic particle testing include:

- Fatigue cracks
- Stress corrosion cracks
- Static failure cracks (overstressed structures)

Types of Components

Examples of materials, structures, and parts that may be inspected using the magnetic particle test method include:

- Ingots
- Billets
- Slabs
- Blooms
- Bar stock
- Sheet
- Rod
- Wire
- Castings
- Shafts (plain, threaded, or splined)
- Welds
- Bearings and bearing races
- Nuts and bolts
- Gears
- Cylinders
- Discs
- Forgings

- Tubular products
- Plate

Industrial Sectors

Magnetic particle testing has many applications throughout industry including but not limited to the following sectors:

- Petrochemical
- Construction
- Aircraft and aerospace
- Automotive
- Defense
- Nuclear
- Transportation
- Shipping (marine)

VIII. ADVANTAGES AND LIMITATIONS

Advantages

The following are advantages of magnetic particle testing as compared to alternative NDT methods.

1. Test results are virtually instantaneous, in that indications will form within one or two seconds of particle application. No developing or processing times are involved.
2. Permanent records of indications can be produced using photography, magnetic rubber, or transparent tape techniques.
3. MT can be applied "in-situ," without the need for an AC power supply, by using permanent magnets or battery-powered yokes.
4. Indications are easy to interpret.
5. The indications formed by the particles closely represent the shape and type of the discontinuity.
6. Training and experience requirements prior to becoming certified are significantly less stringent than for UT, RT, or ET, since MT is a relatively simple process.
7. MT equipment can be much less expensive than other NDT equipment. Depending on the degree of automation or scale of operation, it may also be more economical than many other NDT methods.
8. Virtually any size or shape of component can be inspected.
9. Inspections can be performed during all stages of manufacturing.
10. Test part surface preparation is less critical than with penetrant testing.
11. MT can be used to inspect through metallic and nonmetallic coatings or plating with some techniques. It should be noted, however, that a reduction in sensitivity will occur as the thickness of the coating increases. Maximum coating thickness should be

established through qualification tests or stipulated in customer specifications or code requirements.

12. There are no known personnel hazards associated with the process because the magnetic fields generated are of short duration; however, the usual electric shock, manual lifting, and chemical (petroleum distillate) precautions apply. Additionally, the parts may become heated during the process if high-amperage current is applied for an extended period.
13. Many parts can be inspected simultaneously if using the residual magnetism technique.
14. MT can be automated for certain production line applications.

Limitations

The following are limitations of magnetic particle testing as compared to other NDT methods.

1. It is only effective for the examination of ferromagnetic materials.
2. Discontinuity detection is limited to those at or near the surface.
3. Demagnetization may be required before, between, and after inspections.
4. Discontinuities will only be detected when their major axis interrupts the primary flux lines. This necessitates inspection in more than one direction to assure discontinuity detection regardless of orientation.
5. Some magnetic particle testing techniques may cause damage to the part as a result of arcing or localized overheating of the parts (for example, when using DC prods).
6. Paint and/or coating removal is necessary from localized areas on the part to facilitate good electrical contact when using direct magnetization techniques.
7. Uniform, predictable flux flow through the parts being tested may not be possible due to complex shapes.
8. Nonrelevant indications due to abrupt changes in component profile or local changes in material properties may make interpretation difficult.

IX. GLOSSARY OF KEY TERMS

Alternating current (AC)—Electric current that flows through a conductor in a back and forth manner at specific intervals. It provides the best sensitivity for the detection of discontinuities at the surface.

Background—The general appearance of the surface on which discontinuities are being sought.

Black light—Electromagnetic radiation in the 320 to 400 nanometer wavelength range, which is invisible to humans. Also see *Ultraviolet light.*

Burning—Local overheating of the component at the electrical contact area arising from high resistance and the production of an arc.

Carrier fluid or liquid—The fluid in which magnetic particles are suspended to facilitate their application.

Circumferential magnetization (circular magnetization)—Magnetization that establishes a flux around the periphery of a part.

Coil method—A method of magnetization in which part or all of the component is encircled by a current-carrying coil. (The use of this term is usually restricted to instances in which the component does not form part of a continuous magnetic circuit for the flux generated).

Current induction method—A method of magnetizing in which a circulating current is "induced" into a ring component by the influence of a fluctuating magnetic field that links the component. Also known as indirect magnetization.

Demagnetization—The process by which a part is returned substantially to the near-unmagnetized state.

Demagnetizing coil—A coil of wires carrying alternating current that is used for demagnetization.

Diffuse indications—Indications that are not clearly defined; e.g., indication of subsurface discontinuities.

Direct current (DC)—Electric current that flows through a conductor in only one direction at all times. DC from a battery source has been phased out in favor of "rectified" forms of AC for surface and subsurface discontinuity detection.

Dry particle technique—The application of magnetic particles in dry form (without the use of a liquid carrier).

Ferromagnetic—Having magnetic permeability, which can be considerably greater than that of air and can vary with flux density.

Fluorescence—The ability to absorb electromagnetic radiation with a wavelength outside the human visible spectrum (black light) and reemit electromagnetic radiation within the white light spectrum, usually in the yellow to green range.

Flux—Invisible lines of magnetic force.

Flux density (β)—Magnetic field strength per unit volume within a ferromagnetic test part; expressed in "gauss." (See also *Tesla.*)

Flux field penetration—The ability to establish and drive high-density magnetic lines of force into the test part.

Full-wave rectified current (FWDC)—Electric current that flows through a conductor in one direction only with an increased rate of pulsation surges and drops at specific intervals. FWDC is recommended for effective surface and subsurface discontinuity detection when using wet-suspension techniques.

Half-wave rectified current (HWDC)—Electric current that flows through a conductor in one direction only with pulsating surges and drops at specific intervals—hence the name half-wave. It is most effective for surface and subsurface discontinuity detection when using the dry particle technique due to the vibratory effect produced on the particles.

Hysteresis loop (and related terms)—See Section II.

Linear indication—Any indication having a length dimension at least three times greater than its width (as defined by some codes).

Longitudinal magnetization—Magnetization in which the flux lines are oriented in the part in a direction essentially parallel to its longitudinal axis.

Magnetic domains—Ferrous material atoms or molecules, normally represented as small bar magnets with north and south poles.

Magnetic particle inspection—A nondestructive test method that provides for the detection of linear, surface, and near-surface discontinuities in ferromagnetic test materials.

Magnetic poles—Those parts of a magnet that are the source of the external magnetic field.

Magnetic writing—Spurious indications arising from random local magnetization.

Magnetism—A form of energy directly associated with electrical current and characterized by fields of lines of force.

Magnetizing force (*H*)—Magnetic field strength per unit volume in air, measured in oersteds.

Mercury vapor lamp—A bulb used for producing ultraviolet radiation. (See also *ultraviolet light* and *black light.*)

Particle mobility—The ability to impart activity or motion to the magnetic particles applied to the test surface.

Permeability—The ease with which a material can be magnetized. The ability of a material to conduct magnetic lines of force.

Prods—Hand-held electrodes attached to cables that transmit the magnetizing current from the power supply to the part under examination.

Reluctance—The opposition of a material to conduct magnetic lines of force.

Residual magnetism—The magnetism remaining in a part after the magnetizing force has ceased.

Retentivity—The ability of a material to retain magnetism following magnetization.

Tesla—An expression of flux density. 1 tesla = 10^4 gauss or 1 weber/meter^2.

Ultraviolet light—Electromagnetic radiation in the 200–400 nanometer wavelength range. The 200–320 manometer wavelength range contains harmful UV radiation, which can damage the skin tissue or the eyes. It is essential that this be filtered out using the correct black light filter. (See *black light.*)

Weber—1 weber = 10^8 lines of force. Note: 1 meter^2 = 10,000 cm^2; therefore, there are 10,000 flux lines/cm^2 (1 gauss).

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