תדריך מעבדה – בדיקות לא הורסות

חלק א' - בדיקת צבעים חודרים

1. תקציר:

1. הכרת שיטת הבדיקה ללא הרס באמצעות צבעים חודרים.
2. הכרת הציוד המשמש לביצוע הבדיקה.
3. שימוש בשיטה לזיהוי פגמים בחומר.

* נלקח מאתר האינטרנט
http://www.ndt-ed.org/EducationResources/CommunityCollege/communitycollege.htm

2. רקע תיאורטי*

2.1. Introduction of Penetrant Inspection

Liquid penetrant inspection is a method that is used to reveal surface breaking flaws by bleedout of a colored or fluorescent dye from the flaw (figure 1). The technique is based on the ability of a liquid to be drawn into a "clean" surface breaking flaw by capillary action. After a period of time called the "dwell," excess surface penetrant is removed and a developer applied. This acts as a blotter. It draws the penetrant from the flaw to reveal its presence. Colored (contrast) penetrants require good white light while fluorescent penetrants need to be used in darkened conditions with an ultraviolet "black light".

2.2. Why a Penetrant Inspection Improves the detectability of Flaws.

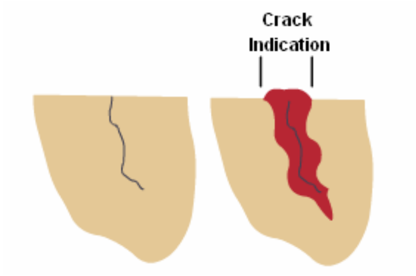


figure 1: bleedout of a colored or fluorescent dye from the flaw

The advantage that a liquid penetrant inspection (LPI) offers over an unaided visual inspection is that it makes defects easier to see for the inspector. There are basically two ways that a penetrant inspection process makes flaws more easily seen. First, LPI produces a flaw indication that is much larger and easier for the eye to detect than the flaw itself. Many flaws are so small or narrow that they are undetectable by the unaided eye. Due to the physical features of the eye, there is a threshold below which objects cannot be resolved. This threshold of visual acuity is around 0.003 inch for a person with 20/20 vision. The second way that LPI improves the detectability of a flaw is that it produces a flaw indication with a high level of contrast between the indication and the background also helping to make the indication more easily seen.

2.3. Basic Processing Steps of a Liquid Penetrant Inspection

2.3.1. Surface Preparation: One of the most critical steps of a liquid penetrant inspection is the surface preparation. The surface must be free of oil, grease, water, or other contaminants that may prevent penetrant from entering flaws. The sample may also require etching if mechanical operations such as machining, sanding, or grit blasting have been performed. These and other mechanical operations can smear metal over the flaw opening and prevent the penetrant from entering.

2.3.2. Penetrant Application: Once the surface has been thoroughly cleaned and dried, the penetrant material is applied by spraying, brushing, or immersing the part in a penetrant bath (figure 2).

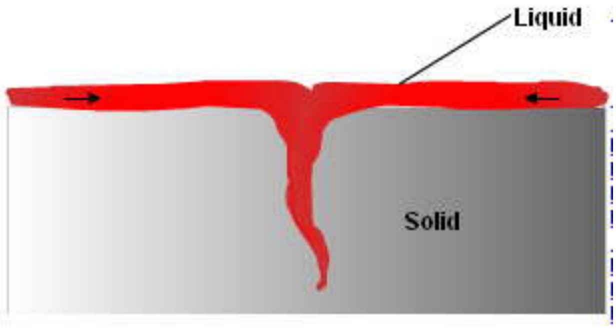


figure 2: the penetrant material is applied

2.3.3. Penetrant Dwell: The penetrant is left on the surface for a sufficient time to allow as much penetrant as possible to be drawn from or to seep into a defect. Penetrant dwell time is the total time that the penetrant is in contact with the part surface. Dwell times are usually recommended by the penetrant producers or required by the specification being followed. The times vary depending on the application, penetrant materials used, the material, the form of the material being inspected, and the type of defect being inspected for. Minimum dwell times typically range from five to 60 minutes. Generally, there is no harm in using a longer penetrant dwell time as long as the penetrant is not allowed to dry. The ideal dwell time is often determined by experimentation and may be very specific to a particular application.

2.3.4. Excess Penetrant Removal: This is the most delicate part of the inspection procedure because the excess penetrant must be removed from the surface of the sample while removing as little penetrant as possible from defects (figure 3). Depending on the penetrant system used, this step may involve cleaning with a solvent, direct rinsing with water, or first treating the part with an emulsifier and then rinsing with water.

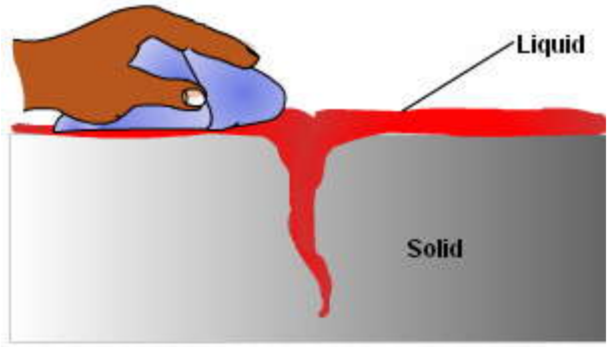


figure 3: The excess penetrant removed from the surface of the sample

2.3.5. Developer Application: A thin layer of developer is then applied to the sample to draw penetrant trapped in flaws back to the surface where it will be visible (figure 4). Developers come in a variety of forms that may be applied by dusting (dry powdered), dipping, or spraying (wet developers).

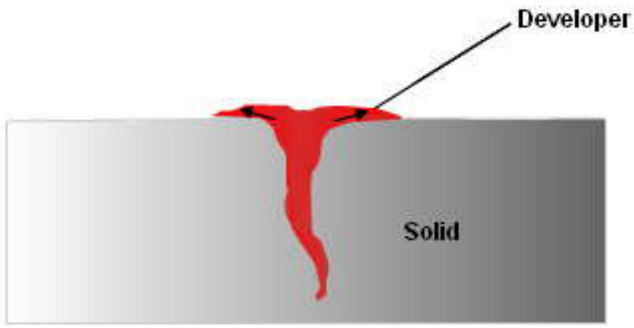


figure 4: Developer Application

2.3.6. Indication Development: The developer is allowed to stand on the part surface for a period of time sufficient to permit the extraction of the trapped penetrant out of any surface flaws. This development time is usually a minimum of 10 minutes. Significantly longer times may be necessary for tight cracks.

2.3.7. Inspection: Inspection is then performed under appropriate lighting to detect indications from any flaws which may be present.

2.3.8. Clean Surface: The final step in the process is to thoroughly clean the part surface to remove the developer from the parts that were found to be acceptable.

2.4. Common Uses of Liquid Penetrant Inspection

Liquid penetrant inspection (LPI) is one of the most widely used nondestructive evaluation (NDE) methods. Its popularity can be attributed to two main factors: its relative ease of use and its flexibility. LPI can be used to inspect almost any material provided that its surface is not extremely rough or porous. Materials that are commonly inspected using LPI include the following:

- Metals (aluminum, copper, steel, titanium, etc.)
- Glass
- Many ceramic materials
- Rubber
- Plastics

Liquid penetrant inspection can only be used to inspect for flaws that break the surface of the sample. Some of these flaws are listed below:

- Fatigue cracks
- Quench cracks
- Grinding cracks
- Overload and impact fractures
- Porosity
- Laps
- Seams
- Pin holes in welds
- Lack of fusion or braising along the edge of the bond line

As mentioned above, one of the major limitations of a penetrant inspection is that flaws must be open to the surface.

2.5. Advantages and Disadvantages of Penetrant Testing

Primary Advantages

- The method has high sensitivity to small surface discontinuities.

- The method has few material limitations, i.e. metallic and nonmetallic, magnetic and nonmagnetic, and conductive and nonconductive materials may be inspected.
- Large areas and large volumes of parts/materials can be inspected rapidly and at low cost.
- Parts with complex geometric shapes are routinely inspected.
- Indications are produced directly on the surface of the part and constitute a visual representation of the flaw.
- Aerosol spray cans make penetrant materials very portable.
- Penetrant materials and associated equipment are relatively inexpensive.

Primary Disadvantages

- Only surface breaking defects can be detected.
- Only materials with a relatively nonporous surface can be inspected.
- Precleaning is critical since contaminants can mask defects.
- Metal smearing from machining, grinding, and grit or vapor blasting must be removed prior to LPI.
- The inspector must have direct access to the surface being inspected.
- Surface finish and roughness can affect inspection sensitivity.
- Multiple process operations must be performed and controlled.
- Post cleaning of acceptable parts or materials is required.
- Chemical handling and proper disposal is required.

2.6. Penetrant Testing Materials

To perform well, a penetrant must possess a number of important characteristics. A penetrant must:

- spread easily over the surface of the material being inspected to provide complete and even coverage.
- be drawn into surface breaking defects by capillary action.
- remain in the defect but remove easily from the surface of the part.
- remain fluid so it can be drawn back to the surface of the part through the drying and developing steps.

- be highly visible or fluoresce brightly to produce easy to see indications.
- not be harmful to the material being tested or the inspector

Certain physical properties of the penetrant materials must be met. Some of these requirements address the safe use of the materials, other requirements address storage and contamination issues, Still others delineate properties that are thought to be primarily responsible for the performance or sensitivity of the penetrants. The properties of penetrant materials include toxicity, flash point, and corrosiveness, surface wetting capability, viscosity, color, brightness, ultraviolet stability, thermal stability, water tolerance, and removability.

Penetrant materials come in two basic types. These types are listed below:

- Type 1 - Fluorescent Penetrants
- Type 2 - Visible Penetrants

figure 5: Fluorescent Penetrants

Fluorescent penetrants (figure 5) contain a dye or several dyes that fluoresce when exposed to ultraviolet radiation. Visible penetrants contain a red dye that provides high contrast against the white developer background. Fluorescent penetrant systems are more sensitive than visible penetrant systems because the eye is drawn to the glow of the fluorescing indication. However, visible penetrants do not require a darkened area and an ultraviolet light in order to make an inspection. Visible penetrants are also less vulnerable to contamination from things such as cleaning fluid that can significantly reduce the strength of a fluorescent indication. Penetrants are then classified by the method used to remove the excess penetrant from the part. The four methods are listed below:

1. Method A - Water Washable
2. Method B - Post-Emulsifiable, Lipophilic
3. Method C - Solvent Removable
4. Method D - Post-Emulsifiable, Hydrophilic

Water washable (Method A) penetrants can be removed from the part by rinsing with water alone. These penetrants contain an emulsifying agent (detergent) that makes it possible to wash the penetrant from the part surface with water alone. Water washable penetrants are sometimes referred to as self-emulsifying systems. Post-emulsifiable penetrants come in two varieties, lipophilic and hydrophilic. In post-emulsifiers, lipophilic systems (Method B), the penetrant is oil soluble and interacts with the oil-based emulsifier to make removal possible. Post-emulsifiable, hydrophilic systems (Method D), use an emulsifier that is a water soluble detergent which lifts the excess penetrant from the surface of the part with a water wash. Solvent removable penetrants require the use of a solvent to remove the penetrant from the part.

3. מיכשור:

- מנורת אור שחור:
- Ultra Violet light, Model No.LH125
- Electric Power 100W, Serial No. 3156
- צבע חודר פלורוסנטי

4. מהלך הניסוי:

קבל ממדריך המעבדה כמה חלקים לבדיקה, בחלקם יש סדקים ובאחרים אין סדקים.
נשתמש בחומרי ניקוי, צבע ומפתח המצויים במיכלי גז כתרסיסים.

1. נקה באופן יסודי את המשטחים המיועדים לבדיקה בחומר הניקוי (שהוא ממס אורגני). השהה את החלקים לייבוש.
2. במנדף, התז על החלקים תרסיס של צבע חודר.
3. השהה את החלקים מכוסים בצבע לחצי שעה לפחות.
4. נגב את שאריות הצבע החודר בנייר סופג או סמרטוט ספוג בחומר הניקוי. היעזר במנורה כחולה (מנורת אולטרה-סגול) כדי לוודא שהסרת את כל הצבע.

5. התז את המפתח על החלקים. השהה לדקה אחת.
6. בדוק ב"אור כחול" קיום פגמים בחלקים שבדקת.

5. הנחיות לדו"ח המסכם:

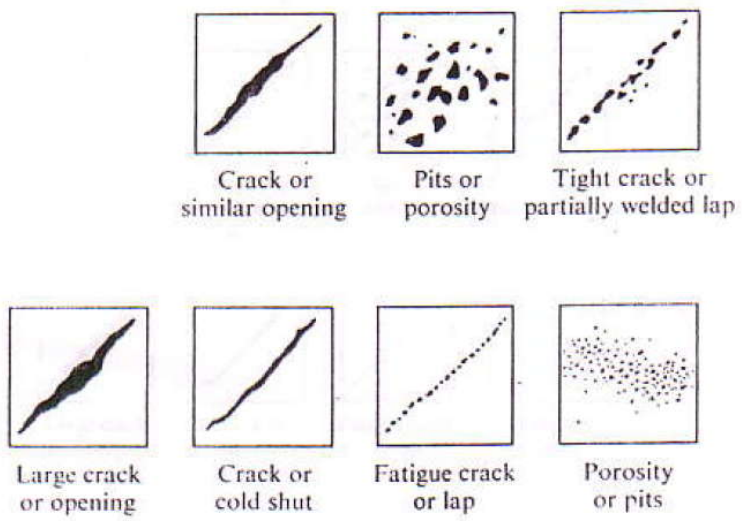
1. תאר את הניסוי שבצעת.
2. מהם היתרונות והמגבלות של שיטת הצבעים החודרים.

6. ביבליוגרפיה

1. http://www.ndt-ed.org/EducationResources/CommunityCollege/communitycollege.htm
2. "Handbook of nondestructive evaluation", Charles J. Hellier, 2001 (TA 417.2.H45),
3. "Introduction to the non-destructive testing of welded joints", R. Halmshaw, 1996 (TA 492.W4H3555).
4. "Non destructive evaluation: a tool in design, manufacturing, and service", Don E.Bray, 1997 (TA 417.2.B63).
5. "Metals Handbook", 10^{th} ed., ASM , Vol.17 , Non Destructive Evaluation and Quality Control, 1990 (TA 459 A5).

**נלקח מקובץ ניסיונות מעבדות שנה ג', הנדסת חומרים, 2007-2008

7. נספחים**



איור 1: סוגי חיוויים שעשויים להתגלות בשיטת הצבעים החודרים ופיענוחם

Table 4-2. Liquid Penetrant Penetration Time (Typical)

MATERIAL	FORM	TYPE OF DISCONTINUITY	TYPES I & II PROCESS (A) WATER-WASHABLE PENETRATION TIME *	TYPES I & II PROCESS (B) POST-EMULSIFIED PENETRATION TIME *	TYPES I & II PROCESS (C) SOLVENT-REMOVABLE PENETRATION TIME *
ALUMINUM	CASTINGS	POROSITY	5 TO 10 MIN	** 5 MIN.	3
		COLD SHUTS	5 TO 15	** 5	3
	EXTRUSIONS & FORGINGS	LAPS	NR***	10	7
	WELDS	LACK OF FUSION	30	5	3
		POROSITY	30	5	3
	ALL	CRACKS	30	10	5
	ALL	FATIGUE CRACKS	NR	30	5
MAGNESIUM	CASTINGS	POROSITY	15	5	3
		COLD SHUTS	15	5	3
	EXTRUSIONS & FORGINGS	LAPS	NR***	10	7
	WELDS	LACK OF FUSION	30	10	5
		POROSITY	30	10	3
	ALL	CRACKS	30	10	5
	ALL	FATIGUE CRACKS	NR	30	7
STEEL	CASTINGS	POROSITY	30	** 10	3
		COLD SHUTS	30	** 10	7
	EXTRUSIONS & FORGINGS	LAPS	NR***	10	7
	WELDS	LACK OF FUSION	60	20	7
		POROSITY	60	20	7
	ALL	CRACKS	30	20	7
	ALL	FATIGUE CRACKS	NR***	30	10
BRASS & BRONZE	CASTINGS	POROSITY	10	* 5	3
		COLD SHUTS	10	* 5	3
	EXTRUSIONS & FORGINGS	LAPS	NR***	10	7
	BRAZED PARTS	LACK OF FUSION	15	10	3
		POROSITY	15	10	3
	ALL	CRACKS	30	10	3
PLASTICS	ALL	CRACKS	5 TO 30	5	5
GLASS	ALL	CRACKS	5 TO 30	5	5
CARBIDE-TIPPED TOOLS		LACK OF FUSION	30	5	3
		POROSITY	30	5	3
		CRACKS	30	20	5
TITANIUM & HIGH TEMP. ALLOYS	ALL		NR***	20 TO 30	15
ALL METALS	ALL	STRESS OR INTER-GRANULAR CORROSION	NR***	240	240

* FOR PARTS HAVING A TEMPERATURE OF 60°F OR HIGHER

** PRECISION CASTINGS ONLY

*** NR - NOT RECOMMENDED

איור 2: זמני השהייה לחדירה של צבעים חודרים לחומרים שונים

חלק ב' - בדיקת זרמי ערבולת

1. תקציר:

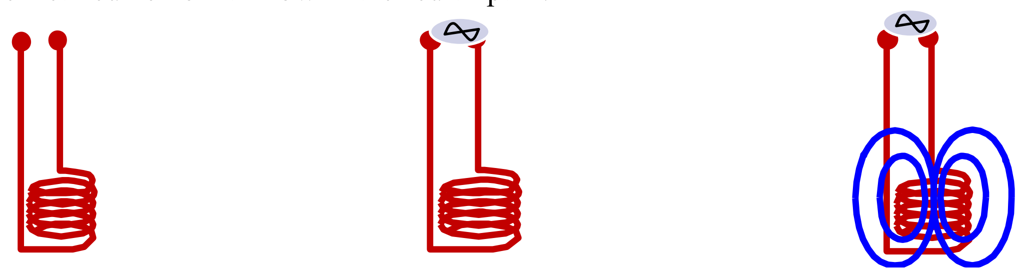
1. הכרת שיטת הבדיקה ללא הרס באמצעות זרמי ערבולת.
2. הכרת הציוד המשמש לביצוע הבדיקה.
3. שימוש בשיטה לזיהוי פגמים בחומר ולמדידות של מוליכות ועובי החומר.

*נלקח מאתר האינטרנט :
http://www.ndt-ed.org/EducationResources/CommunityCollege/communitycollege.htm

2. רקע תיאורטי*

2.1. Basic Principles of Eddy Current Inspection

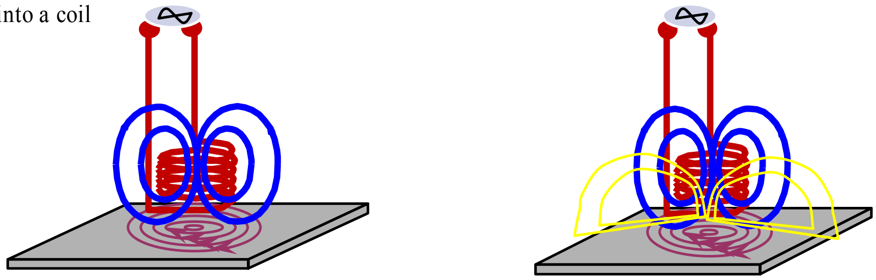
Eddy currents are created through a process called electromagnetic induction. When alternating current is applied to the conductor, such as copper wire, a magnetic field develops in and around the conductor. This magnetic field expands as the alternating current rises to maximum and collapses as the current is reduced to zero. If another electrical conductor is brought into the close proximity to this changing magnetic field, current will be induced in this second conductor. Eddy currents are induced electrical currents that flow in a circular path.



In order to generate eddy currents for an inspection a "probe" is used. Inside the probe is a length of electrical conductor which is formed into a coil

Alternating current is allowed to flow in the coil at a frequency chosen by the technician for the type of test involved.

A dynamic expanding and collapsing magnetic field forms in and around the coil as the alternating current flows through the coil.



A dynamic expanding and collapsing magnetic field forms in and around the coil as the alternating current flows through the coil.

Eddy currents flowing in the material will generate their own "secondary" magnetic field which will oppose the coil's "primary" magnetic field.

Figure 1: The process of electromagnetic induction

and measurements that can be performed. In the proper circumstances, eddy currents can be used for:

- Crack detection
- Material thickness measurements
- Coating thickness measurements
- Conductivity measurements for:
  - Material identification
  - Heat damage detection
  - Case depth determination
  - Heat treatment monitoring

Some of the advantages of eddy current inspection include:

- Sensitive to small cracks and other defects
- Detects surface and near surface defects
- Inspection gives immediate results
- Equipment is very portable
- Method can be used for much more than flaw detection
- Minimum part preparation is required
- Test probe does not need to contact the part
- Inspects complex shapes and sizes of conductive materials

Some of the limitations of eddy current inspection include:

1. Only conductive materials can be inspected
2. Surface must be accessible to the probe
3. Skill and training required is more extensive than other techniques
4. Surface finish and roughness may interfere
5. Reference standards needed for setup
6. Depth of penetration is limited
7. Flaws such as delaminations that lie parallel to the probe coil winding and probe scan direction are undetectable.

2.2. Present State of Eddy Current Inspection

Eddy current inspection is used in a variety of industries to find defects and make measurements. One of the primary uses of eddy current testing is for defect detection when the nature of the defect is well understood. In general, the technique is used to inspect a relatively small area and the probe design and test parameters must be established with a good understanding of the flaw that is to be detected. Since eddy currents tend to concentrate at the surface of a material, they can only be used to detect surface and near surface defects.

In thin materials such as tubing and sheet stock, eddy currents can be used to measure the thickness of the material. This makes eddy current a useful tool for detecting corrosion damage and other damage that causes a thinning of the material. The technique is used to make corrosion thinning measurements on aircraft skins and in the walls of tubing used in assemblies such as heat exchangers. Eddy current testing is also used to measure the thickness of paints and other coatings.

Eddy currents are also affected by the electrical conductivity and magnetic permeability of materials. Therefore, eddy current measurements can be used to sort materials and to tell if a material has seen high temperatures or been heat treated, which changes the conductivity of some materials.

2.3. Induction and Inductance

2.3.1. Induction

In 1824, Oersted discovered that current passing though a coil created a magnetic field capable of shifting a compass needle. Seven years later, Faraday and Henry discovered just the opposite. They noticed that a moving magnetic field would induce current in an electrical conductor. This process of generating electrical current in a conductor by placing the conductor in a changing magnetic field is called **electromagnetic induction** or just **induction**. It is called induction because the current is said to be induced in the conductor by the magnetic field.

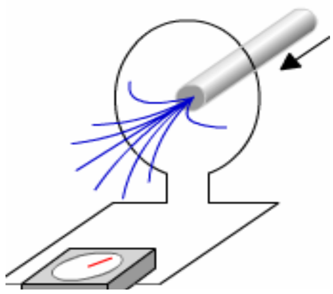


Figure 2: electromagnetic induction

Faraday also noticed that the rate at which the magnetic field changed also had an effect on the amount of current or voltage that was induced. **Faraday's Law** for an uncoiled conductor states that the amount of induced voltage is proportional to the rate of change of flux lines cutting the conductor. Faraday's Law for a straight wire is shown below.

$$V_L = \frac{d\phi}{dt}$$

Where:

VL = the induced voltage in volts

dø/dt = the rate of change of magnetic flux in webers/second

Induction is measured in unit of **Henries (H)** which reflects this dependence on the rate of change of the magnetic field. One henry is the amount of inductance that is required to generate one volt of induced voltage when the current is changing at the rate of one ampere per second.

2.3.2. Inductance

When induction occurs in an electrical circuit and affects the flow of electricity it is called **inductance. Self-inductance**, or simply inductance, is the property of a circuit whereby a change in current causes a change in voltage in the same circuit. When one circuit induces current flow in a second nearby circuit, it is known as **mutual-inductance**.

The image to the right shows an example of mutual-inductance. When an AC current is flowing through a piece of wire in a circuit, an electromagnetic field is produced that is constantly growing and shrinking and changing direction due to the constantly changing current in the wire. This changing magnetic field will induce electrical current in another wire or circuit that is brought close to the wire in the primary circuit. The current in the second wire will also be AC and in fact will look very similar to the current flowing in the first wire. An electrical transformer uses inductance to change the voltage of electricity into a more useful level. In nondestructive testing, inductance is used to generate eddy currents in the test piece.

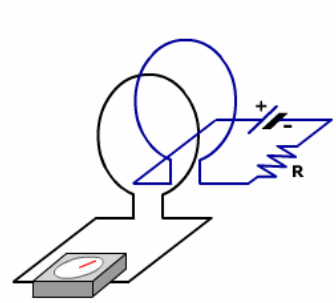


Figure 3: mutual-inductance.

2.4. Self-Inductance and Inductive Reactance

The property of self-inductance is a particular form of electromagnetic induction. Self inductance is defined as the induction of a voltage in a current-carrying wire when the current in the wire itself is changing. In the case of self-inductance, the magnetic field created by a changing current in the circuit itself induces a voltage in the same circuit. Therefore, the voltage is self-induced.

The term inductor is used to describe a circuit element possessing the property of inductance and a coil of wire is a very common inductor. In circuit diagrams, a coil or wire is usually used to indicate an inductive component. Taking a closer look at a coil will help understand the reason that a voltage is induced in a wire carrying a changing current. The alternating current running through the coil creates a magnetic field in and around the coil that is increasing and decreasing as the current changes. The magnetic field forms concentric loops that surround the wire and join to form larger loops that surround the coil as shown in the image below. When the current increases in one loop the expanding magnetic field will cut across some or all of the neighboring loops of wire, inducing a voltage in these loops. This causes a voltage to be induced in the coil when the current is changing.

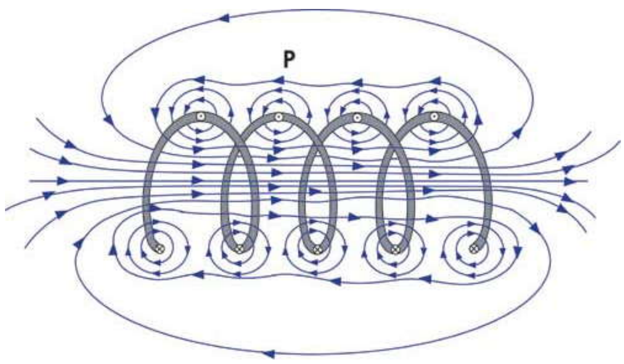


Figure 4: self –inductance in a coil

By studying this image of a coil, it can be seen that the number of turns in the coil will have an effect on the amount of voltage that is induced into the circuit. Increasing the number of turns or the rate of change of magnetic flux increases the amount of induced voltage. Therefore, **Faraday's Law** must be modified for a coil of wire and becomes the following.

$$V_L = N\frac{d\phi}{dt}$$

Where:

V_L = induced voltage in volts

N = number of turns in the coil

dø/dt = rate of change of magnetic flux in webers/second

The equation simply states that the amount of induced voltage (V_L) is proportional to the number of turns in the coil and the rate of change of the magnetic flux (dø/dt). In other words, when the frequency of the flux is increased or the number of turns in the coil is increased, the amount of induced voltage will also increase. In a circuit, it is much easier to measure current than it is to measure magnetic flux, so the following equation can be used to determine the induced voltage if the inductance and frequency of the current are known. This equation can also be reorganized to allow the inductance to be calculated when the amount of inducted voltage can be determined and the current frequency is known.

$$V_L = L\frac{di}{dt}$$

Where:

V_L = the induced voltage in volts

L = the value of inductance in henries

di/dt = the rate of change of current in amperes per second

2.4.1. Lenz's Law

Soon after Faraday proposed his law of induction, Heinrich Lenz developed a rule for determining the direction of the induced current in a loop. Basically, **Lenz's law states that an induced current has a direction such that its magnetic field opposes the change in magnetic field that induced the current**. This means that the current induced in a conductor will oppose the change in current that is causing the flux to change. Lenz's law is important in understanding the property of inductive reactance, which is one of the properties measured in eddy current testing.

2.4.2. Inductive Reactance

The reduction of current flow in a circuit due to induction is called **inductive reactance.** By taking a closer look at a coil of wire and applying Lenz's law, it can be seen how inductance reduces the flow of current in the circuit. In the image below, the direction of the primary current is shown in red, and the magnetic field generated by the current is shown in blue. The direction of the magnetic field can be determined by taking your right hand and pointing your thumb in the direction of the current. Your fingers will then point in the direction of the magnetic field. It can be seen that the magnetic field from one loop of the wire will cut across the other loops in the coil and this will induce current flow (shown in green) in the circuit. According to Lenz's law, the induced current must flow in the opposite direction of the primary current. The induced current working against the primary current results in a reduction of current flow in the circuit. It should be noted that the inductive reactance will increase if the number of winds in the coil is increased since the magnetic field from one coil will have more coils to interact with

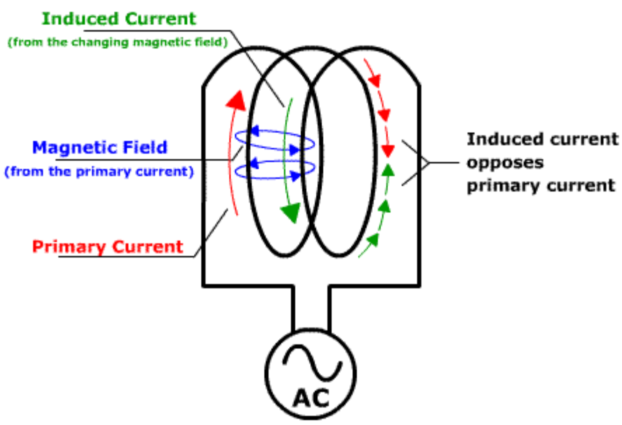


Figure5: inductive reactance

Since inductive reactance reduces the flow of current in a circuit, it appears as an energy loss just like resistance. However, it is possible to distinguish between resistance and inductive reactance in a circuit by looking at the timing between the sine waves of the voltage and current of the alternating current. In an AC circuit that contains only resistive components, the voltage and the current will be in-phase, meaning that the peaks and valleys of their sine waves will occur at the same time.

When there is inductive reactance present in the circuit, the phase of the current will be shifted so that its peaks and valleys do not occur at the same time as those of the voltage.

2.5. Mutual Inductance (The Basis for Eddy Current Inspection)

The magnetic flux through a circuit can be related to the current in that circuit and the currents in other nearby circuits, assuming that there are no nearby permanent magnets. Consider the following two circuits.

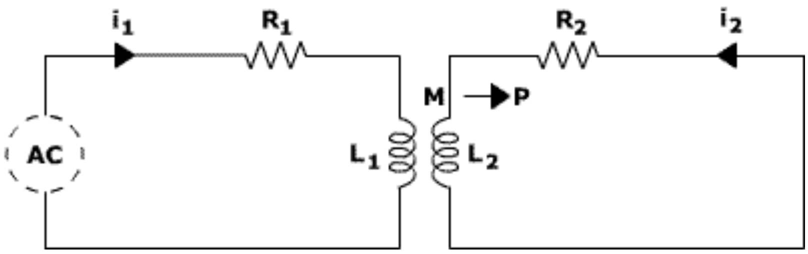


Figure 6: mutual-inductance.

The magnetic field produced by circuit 1 will intersect the wire in circuit 2 and create current flow. The induced current flow in circuit 2 will have its own magnetic field which will interact with the magnetic field of circuit 1. At some point P, the magnetic field consists of a part due to i_1 and a part due to i_2. These fields are proportional to the currents producing them. The coils in the circuits are labeled L_1 and L_2 and this term represents the self inductance of each of the coils. The values of L_1 and L_2 depend on the geometrical arrangement of the circuit (i.e. number of turns in the coil) and the conductivity of the material. The constant M, called the **mutual inductance** of the two circuits, is dependent on the geometrical arrangement of both circuits. In particular, if the circuits are far apart, the magnetic flux through circuit 2 due to the current i_1 will be small and the mutual inductance will be small. L_2 and M are constants.

We can write the flux, B through circuit 2 as the sum of two parts.

$$B_2 = L_2 i_2 + i_1 M$$

An equation similar to the one above can be written for the flux through circuit 1.

$$B_1 = L_1 i_1 + i_2 M$$

Though it is certainly not obvious, it can be shown that the mutual inductance is the same for both circuits. Therefore, it can be written as follows:

$$M_{1,2}=M_{2,1}$$

2.5.1. How is mutual induction used in eddy current inspection?

In eddy current inspection, the eddy currents are generated in the test material due to mutual induction. The test probe is basically a coil of wire through which alternating current is passed. The second circuit can be any piece of conductive material (figure 7(a)).

When alternating current is passed through the coil, a magnetic field is generated in and around the coil. When the probe is brought in close proximity to a conductive material, such as aluminum, the probe's changing magnetic field generates current flow in the material. The induced current flows in closed loops in planes perpendicular to the magnetic flux. They are named **eddy currents** because they are thought to resemble the eddy currents that can be seen swirling in streams (figure 7(b)).

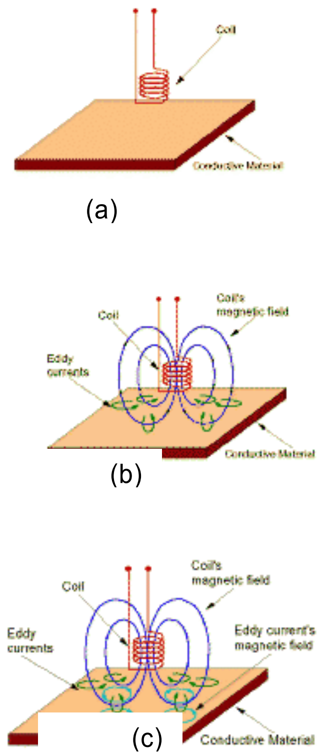
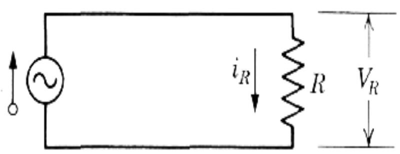


Figure 7: mutual inductance

The eddy currents produce their own magnetic fields that interact with the primary magnetic field of the coil. By measuring changes in the resistance and inductive reactance of the coil, information can be gathered about the test material. This information includes the electrical conductivity and magnetic permeability of the material, the amount of material cutting through the coils magnetic field, and the condition of the material (i.e. whether it contains cracks or other defects.) The distance that the coil is from the conductive material is called **liftoff,** and this distance affects the mutual-inductance of the circuits. Liftoff can be used to make measurements of the thickness of nonconductive coatings, such as paint, that hold the probe a certain distance from the surface of the conductive material (figure 7(c)).

2.6. Circuits and Phase

A circuit can be thought of as a closed path in which current flows through the components that make up the circuit. The current (i) obeys Ohm's Law. The simple circuit below (figure 8 (a)) consists of a voltage source (in this case an alternating current voltage source) and a resistor. The graph below (figure 8(b)) shows the value of the voltage and the current for this circuit over a period of time. This graph shows one complete cycle of an alternating current source. From the graph, it can be seen that as the voltage increases, the current does the same. The voltage and the current are said to be "in-phase" since their zero, peak, and valley points occur at the same time. They are also directly proportional to each other.



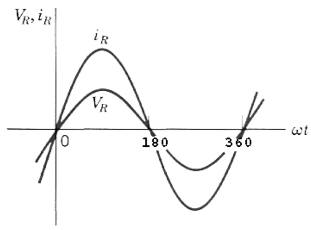


Figure 8 : A circuit consists of voltage source (a), The circuit diagram shows the value of the voltage and the current for this circuit over a period of time (b).

In the circuit below (figure 9(a)), the resistive component has been replaced with an inductor. When inductance is introduced into a circuit, the voltage and the current will be "out-of-phase," meaning that the voltage and current do not cross zero, or reach their peaks and valleys at the same time. When a circuit has an inductive component, the current (i_L) will lag the voltage by one quarter of a cycle. One cycle is often referred to as 360°, so it can be said that the current lags the voltage by 90°. This phase shift occurs because the inductive reactance changes with changing current. Recall that it is the changing magnetic field caused by a changing current that produces inductive reactance. When the change in current is greatest, inductive reactance will be the greatest, and the voltage across the inductor will be the highest. When the change in current is zero, the inductive reactance will be zero and the voltage across the inductor will be zero. Be careful not to confuse the amount of current with the amount of change in the current. Consider the points where the current reaches it peak amplitude and changes direction in the graph below (figure 9(b)) (0^o, 180^o, and 360^o). As the current is changing directions, there is a split second when the **change in current** is zero. Since the change in current is zero, no magnetic field is generated to produce the inductive reactance. When the inductive reactance is zero, the voltage across the inductor is zero.

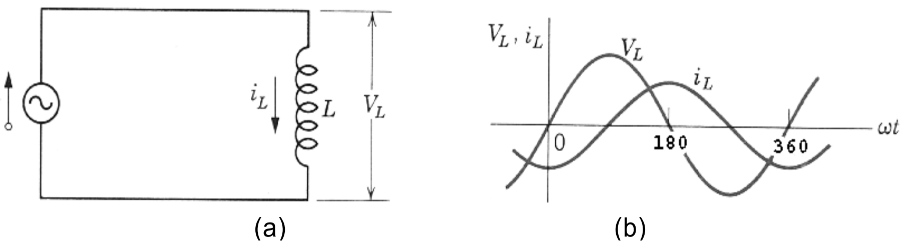


Figure 9 : A circuit consists of voltage source, the resistive component has been replaced with an inductor (a), The circuit diagram shows the value of the voltage and the current for this circuit over a period of time.

The resistive and inductive components are of primary interest in eddy current testing since the test probe is basically a coil of wire, which will have both resistance and inductive reactance. However, there is a small amount of capacitance in the circuits so a mention is appropriate. This simple circuit below (figure 10) consists of an alternating current voltage source and a capacitor. Capacitance in a circuit caused the current (i_c) to lead the voltage by one quarter of a cycle (90^o current lead).

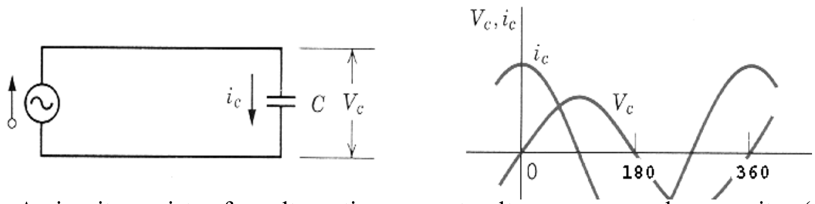
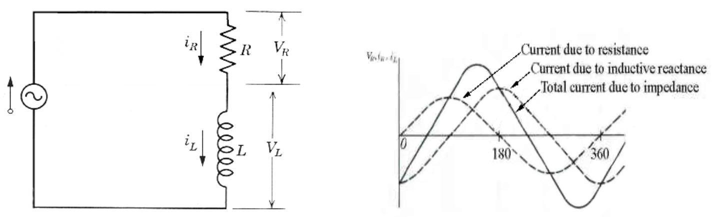


Figure 10 : A circuit consists of an alternating current voltage source and a capacitor (a), The circuit diagram shows the value of the voltage and the current for this circuit over a period of time (b).

When there is both resistance and inductive reactance (and/or capacitance) in a circuit, the combined opposition to current flow is known as impedance.

2.7. Impedance

Electrical **Impedance (Z)**, is the total opposition that a circuit presents to alternating current. Impedance is measured in ohms and may include **resistance (R)**, i**nductive reactance (X_L)**, and **capacitive reactance (X_C)**. However, the total impedance is not simply the algebraic sum of the resistance, inductive reactance, and capacitive reactance. Since the inductive reactance and capacitive reactance are 90^o out of phase with the resistance and, therefore, their maximum values occur at different times, vector addition must be used to calculate impedance. In the image below (figure 11(a)), a circuit diagram is shown that represents an eddy current inspection system. The eddy current probe is a coil of wire so it contains resistance and inductive reactance when driven by alternating current. The capacitive reactance can be dropped as most eddy current probes have little capacitive reactance. The solid line in the graph below (figure 11(b)) shows the circuit's total current, which is affected by the total impedance of the circuit. The two dashed lines represent the portion of the current that is affected by the resistance and the inductive reactance components individually. It can be seen that the resistance and the inductive reactance lines are 90^o out of phase, so when combined to produce the impedance line, the phase shift is somewhere between zero and 90^o. The phase shift is always relative to the resistance line since the resistance line is always in-phase with the voltage. If more resistance than inductive reactance is present in the circuit, the impedance line will move toward the resistance line and the phase shift will decrease. If more inductive reactance is present in the circuit, the impedance line will shift toward the inductive reactance line and the phase shift will increase.



(a) (b)

Figure 11 : a circuit diagram that represents an eddy current inspection system (a), The circuit diagram shows the circuit's total current, which is affected by the total impedance of the circuit (b)

The relationship between impedance and its individual components (resistance and inductive reactance) can be represented using a vector (figure 12). The amplitude of the resistance component is shown by a vector along the x-axis and the amplitude of the inductive reactance is shown by a vector along the y-axis. The amplitude of the impedance is shown by a vector that stretches from zero to a point that represents both the resistance value in the x-direction and the inductive reactance in the y-direction.

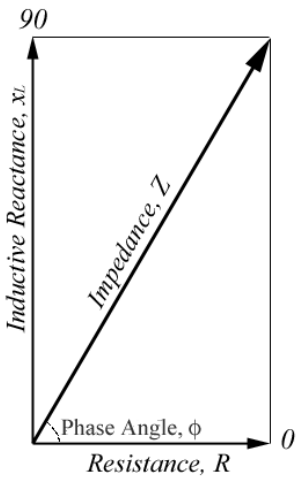


Figure 12 : The relationship between impedance and its individual components

Eddy current instruments with impedance plane displays present information in this format. The impedance in a circuit with resistance and inductive reactance can be calculated using the following equation. If capacitive reactance was present in the circuit, its value would be added to the inductance term before squaring

$$Z = \sqrt{\left(X_L^2 + R^2\right)}$$

The **phase angle** of the circuit can be calculated using the equation below. If capacitive reactance was present in the circuit, its value would be subtracted from the inductive reactance term.

$$\tan\varphi = \frac{X_L}{R}$$

2.8. Depth of Penetration & Current Density

Eddy currents are closed loops of induced current circulating in planes perpendicular to the magnetic flux. They normally travel parallel to the coil's winding and flow is limited to the area of the inducing magnetic field. Eddy currents concentrate near the surface adjacent to an excitation coil and their strength decreases with distance from the coil. Eddy current density decreases exponentially with depth. This phenomenon is known as the skin effect. The skin effect arises when the eddy currents flowing in the test object at any depth produce magnetic fields which oppose the primary field, thus reducing the net magnetic flux and causing a decrease in current flow as the depth increases. Alternatively, eddy currents near the surface can be viewed as shielding the coil's magnetic field, thereby weakening the magnetic field at greater depths and reducing induced currents. The depth that eddy currents penetrate into a material is affected by the frequency of the excitation current, the electrical conductivity and the magnetic permeability of the specimen (see figure 13). The depth of penetration decreases with increasing frequency and increasing conductivity and magnetic permeability. The depth at which eddy current density has decreased to 1/e, or about 37% of the surface density, is called the standard depth of penetration (δ). The word 'standard' denotes plane wave electromagnetic field excitation within the test sample (conditions which are rarely achieved in practice). Although eddy currents penetrate deeper than one standard depth of penetration, they decrease rapidly with depth. At two standard depths of penetration (2δ), eddy current density has decreased to 1/e squared or 13.5% of the surface density. At three depths (3δ), the eddy current density is down to only 5% of the surface density.

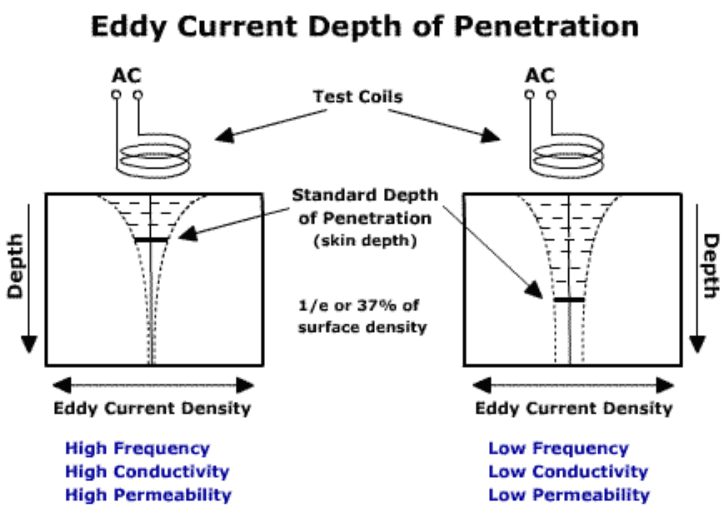


Figure 13: The depth that eddy currents penetrate into a material

Since the sensitivity of an eddy current inspection depends on the eddy current density at the defect location, it is important to know the strength of the eddy currents at this location. When attempting to locate flaws, a frequency is often selected which places the expected flaw depth within one standard depth of penetration. This helps to assure that the strength of the eddy currents will be sufficient to produce a flaw indication. Alternately, when using eddy currents to measure the electrical conductivity of a material, the frequency is often set so that it produces three standard depths of penetration within the material. This helps to assure that the eddy currents will be so weak at the back side of the material that changes in the material thickness will not affect the eddy current measurements. The equation for the calculation of the standard depth of penetration:

$$\delta \approx \frac{1}{\sqrt{\pi f \mu \sigma}}$$

Where:

δ = Standard Depth of Penetration (mm)

π = 3.14

f = Test Frequency (Hz)

μ = Magnetic Permeability (H/mm)

σ = Electrical Conductivity (% IACS)

2.9. Probes - Mode of Operation

Eddy current probes are available in a large variety of shapes and sizes (figure 14). In fact, one of the major advantages of eddy current inspection is that probes can be custom designed for a wide variety of applications.

Figure 14 : Eddy current probes

Eddy current probes are classified by the configuration and mode of operation of the test coils. The configuration of the probe generally refers to the way the coil or coils are packaged to best "couple" to the test area of interest.

The mode of operation of a probe generally falls into one of four categories: absolute, differential, reflection and hybrid. Each of these classifications will be discussed in more detail below.

2.9.1. Absolute Probes

Absolute probes generally have a single test coil that is used to generate the eddy currents and sense changes in the eddy current field (figure 15). AC is passed through the coil and this sets up an expanding and collapsing magnetic field in and around the coil. When the probe is positioned next to a conductive material, the changing magnetic field generates eddy currents within the material. The generation of the eddy currents takes energy from the coil and this appears as an increase in the electrical resistance of the coil. The eddy currents generate their own magnetic field that opposes the magnetic field of the coil and this changes the inductive reactance of the coil. By measuring the absolute change in impedance of the test coil, much information can be gained about the test material. Absolute coils can be used for flaw detection, conductivity measurements, liftoff measurements and thickness measurements. They are widely used due to their versatility.

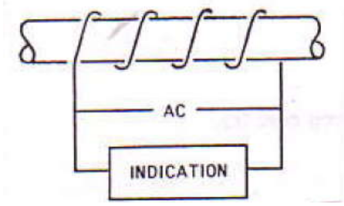


Figure 15 : Absolute probes

2.9.2. Differential Probes

Differential probes have two active coils usually wound in opposition (see figure 17). When the two coils are over a flaw-free area of test sample, there is no differential signal developed between the coils since they are both inspecting identical material. However, when one coil is over a defect and the other is over good material, a differential signal is produced. They have the advantage of being very sensitive to defects yet relatively insensitive to slowly varying properties such as gradual dimensional or temperature variations. Probe wobble signals are also reduced with this probe type. There are also disadvantages to using differential probes. Most notably, the signals may be difficult to interpret. For example, if a flaw is longer than the spacing between the two coils, only the leading and trailing edges will be detected due to signal cancellation when both coils sense the flaw equally.

2.10. Probes – Configurations

2.10.1. Surface Probes

Surface probes (see figure 16) are usually designed to be handheld and are intended to be used in contact with the test surface. Surface probes generally consist of a coil of very fine wire encased in a protective housing. The size of the coil and shape of the housing are determined by the intended use of the probe. Most of the coils are wound so that the axis of the coil is perpendicular to the test surface. This coil configuration is sometimes referred to as a pancake coil and is good for detecting surface discontinuities that are oriented perpendicular to the test surface.

Discontinuities, such as delaminations, that are in a parallel plane to the test surface will likely go undetected with this coil configuration. Wide surface coils are used when scanning large areas for relatively large defects. They sample a relatively large area and allow for deeper penetration. Since they do sample a large area, they are often used for conductivity tests to get more of a bulk material measurement. However, their large sampling area limits their ability to detect small discontinuities. Pencil probes have a small surface coil that is encased in a long slender housing to permit inspection in restricted spaces. They are available with a straight shaft or with a bent shaft, which facilitates easier handling and use in applications such as the inspection of small diameter bores. Pencil probes are prone to wobble due to their small base and sleeves are sometimes used to provide a wider base

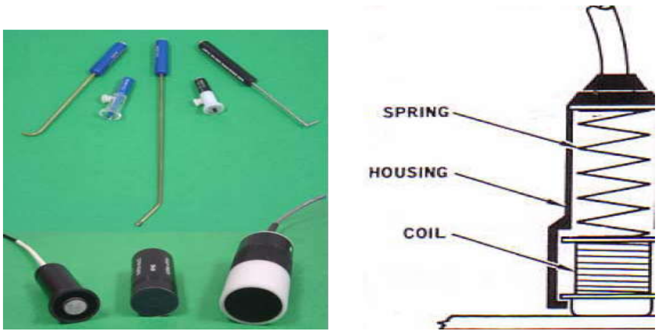


Figure 16 : Surface probes

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2.11. Inspection Applications:

2.11.1. Conductivity Measurements

One of the uses of eddy current instruments is for the measurement of electrical conductivity. The value of the electrical conductivity of a metal depends on several factors, such as its chemical composition and the stress state of its crystalline structure. Therefore, electrical conductivity information can be used for sorting metals, checking for proper heat treatment, and inspecting for heat damage. The technique usually involves nulling an absolute probe in air and placing the probe in contact with the sample surface. For nonmagnetic materials, the change in impedance of the coil can be correlated directly to the conductivity of the material. The technique can be used to easily sort magnetic materials from nonmagnetic materials but it is difficult to separate the conductivity effects from the magnetic permeability effects, so conductivity measurements are limited to nonmagnetic materials. It is important to control factors that can affect the results such as the inspection temperature and the part geometry. Conductivity changes with temperature so measurements should be made at a constant temperature and adjustments made for temperature variations when necessary. The thickness of the specimen should generally be greater than three standard depths of penetration. This is so the eddy currents at the back surface of the sample are sufficiently weaker than the variations in the specimen thickness that are not seen in the measurements. Generally large surface probes are used to get a value for a relatively large sample area. The instrument is usually setup such that a ferromagnetic material produces a response that is nearly vertical. Then, all conductive but nonmagnetic materials will produce a trace that moves down and to the right as the probe is moved toward the surface. When the probe is brought near a conductive but nonmagnetic material, the coil's inductive reactance goes down since the magnetic field from the eddy currents opposes the magnetic field of the coil. The resistance in the coil increases since it takes some of the coil's energy to generate the eddy currents and this appears as additional resistance in the circuit. As the conductivity of the materials being tested increases, the resistance losses will be less and the inductive reactance changes will be greater. Therefore, the signals will become more vertical as the conductivity increases.

2.11.1.1. Conductivity Measurements for the Verification of Heat Treatment

With some materials, such as solution heat treatable aluminum alloys, conductivity measurements are often made verifying that parts and materials have received the proper heat treatment. High purity aluminum is soft and ductile, and gains strength and hardness with the addition of alloying elements. A few such aluminum alloys are the 2000 series (2014, 2024, etc.), 6000 series (6061, 6063, etc.), and 7000 series (7050, 7075, etc.). The 2xxx series aluminum alloys have copper, the 6xxx series have magnesium, and the 7xxx have zinc as their major alloying elements. Heat treatment of aluminum alloys is accomplished in two phases - solution heat treatment and then aging. In the solution heat treatment step, the alloys are heated to an elevated temperature to dissolve the alloying elements into solution. The metal is then rapidly cooled or quenched to "freeze" the atoms of the alloying elements in the lattice structure of the aluminum. This distorts and stresses the structure, making electron movement more difficult, thereby decreasing the electrical conductivity. In this condition, the alloys are still relatively soft but start to gain strength as the alloying elements begin to precipitate out of solution to form extremely small particles that impede the movement of dislocations within the material. The formation of the precipitates can be controlled for many alloys by heating and holding the material at an elevated temperature for a period of time (artificial aging). As the alloying elements precipitate out of solid solution, the conductivity of the material gradually increases. By controlling the amount of precipitated particles within the aluminum, the properties can be controlled to produce peak strength or some combinations of strength and corrosion resistance. Sometimes, the material must be annealed or put into the softest, most ductile condition possible in order to perform forming operations. Annealing allows all of the alloying elements to precipitate out of solution to form a coarse, widely spaced precipitate. The electrical conductivity is greatest when the material is in the annealed condition.

2.11.2. Thickness Measurements of Thin Material

2.11.2.1. Thickness Measurement of Thin Conductive Layers

It is possible to measure the thickness of a thin layer of metal on a metallic substrate, provided the two metals have widely differing electrical conductivities (i.e. silver on lead where σ= 67 and 10 MS/m, respectively). A frequency must be selected such that there is complete eddy current penetration of the layer, but not of the substrate itself. The method has also been used successfully for measuring thickness of very thin protective coatings of ferromagnetic metals (i.e. chromium and nickel) on non-ferromagnetic metal bases.

2.11.2.2. Thickness Measurements of Nonconducting Coatings on Conductive Materials

The thickness of nonmetallic coatings on metal substrates can be determined simply from the effect of liftoff on impedance (figure 17). This method has widespread use for measuring thickness of paint and plastic coatings. The coating serves as a spacer between the probe and the conductive surface. As the distance between the probe and the conductive base metal increases, the eddy current field strength decreases because less of the probe's magnetic field can interact with the base metal. Thicknesses between 0.5 and 25 µm can be measured to an accuracy between 10% for lower values and 4% for higher values. Contributions to impedance changes due to conductivity variations should be phased out, unless it is known that conductivity variations are negligible, as normally found at higher frequencies.

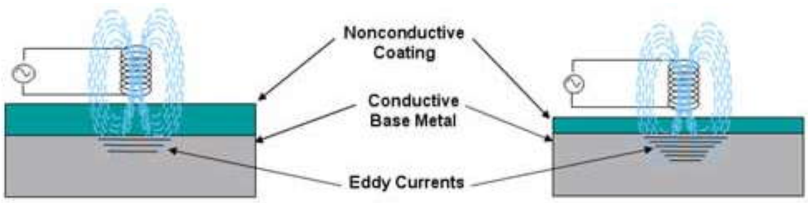


Figure 17: thickness measurements of nonconducting coatings on metal substrates

3. מכשור.

בניסוי נעשה שימוש בשני מכשירים: מכשיר בעל סליל יחיד Multiitest EM 2100 (ראה figure 19) המייצר זרם חילופין בתדירות 240 KHz ומכשיר Multiitest EM 3100 המייצר זרם חילופין בתדירות 2000 KHz והוא בעל סליל למתח ישר המיועד לחומרים פרומגנטיים.

4. מהלך הניסוי:

4.1. בדיקת מוליכות

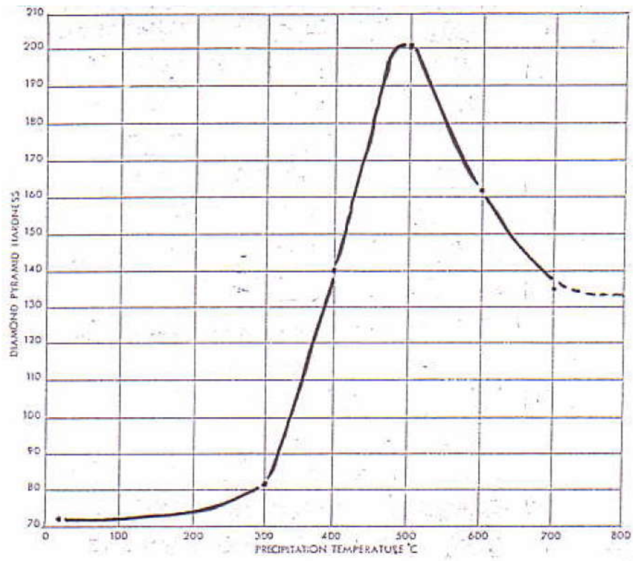
4.2. על גבי בוחש מגנטי (המפעיל זרמי מערבולת) הנח צלוחית המכילה שמן סיכה (לחיכוך נמוך). בצלוחית הנח דיסקות העשויות נחושת, אלומיניום ופליז. מדוד את מספר הסיבובים במשך זמן מוקצב של 15 שניות שמבצעת כל אחת מהדיסקות.

- כייל את המכשיר EM 2100 באמצעות דגמי הכיול מנחושת ועופרת: הבא את המכשיר למצב בו יראה מוליכות 110 IACS לנחושת ומוליכות 8 IACS לעופרת.
- בדוק את המוליכות של דגמי המתכות הבאים: אלומיניום, נחושת, פליז ועופרת.

- בדוק את המוליכות של סדרת דגמים של הנתך Kunial brass (Cu-20%Zn, 6%Ni, 1.5%Al) שעברו טיפולי המסה וזיקון למשך שעתיים בטמפרטורות המפורטות בטבלה :

מורפה	300°C	400°C	500°C	600°C	700°C

הקושי של הדגמים כפונקציה של טמפרטורת הזיקון נתון באיור 1.



איור 2 : קושי כפונקציה של טמפרטורת הזיקון

השווה בין המגמה של הקשיות והמוליכות החשמלית כתלות בטמפרטורה.

- העבר את המכשיר למצב IACS 25-65 ובדוק כיול. בדוק את המוליכות של סדרת דגמי פליז בריכוזים שונים של אבץ : Cu-0,5,10,15,20,35,40%Zn.

4.3. בדיקת עובי

- בדוק את המוליכות של פח נחושת דק ופח נחושת עבה.
- בדוק את המוליכות של לוחות אלומיניום מצופים סרטי דבק בעוביים שונים. האם יש בדרך זו אפשרות לקבוע עובי של ציפוי לא מוליך על מתכת?

4.4. בדיקת פגמים

מכשיר EM 3100 משמש לזיהוי אי אחידויות בחומרים פרו-מגנטיים.

אפס את הזרם בשני הסלילים P ו-X והשתמש במכשיר לזיהוי סדקים בדגם פלדה.

5. הנחיות לדו"ח מסכם.

1. תאר את הניסויים שבצעת.

2. הסבר את ההשפעות של הקשיית מסיסות, עיבוד בקור והמסה וזיקון על המוליכות החשמלית.

4. מהם היתרונות והחסרונות של שיטת זרמי ערבולת.

6. ביבליוגרפיה:

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**נלקח מקובץ ניסיונות מעבדות שנה ג', הנדסת חומרים, 2007-2008 .

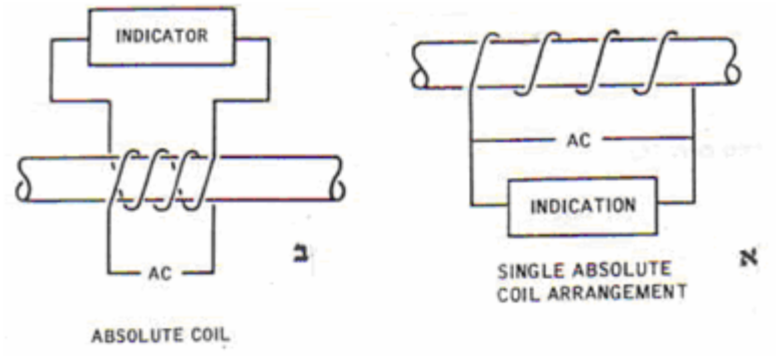
7. נספחים**

7.1. שיטות הבדיקה:

אפשר להשתמש בזרמי מערבולת בכמה שיטות: בדיקת זרמי מערבולת היא בדיקה השוואתית. כדי לקבוע קיום פגם, מוליכות או עובי בודקים דגם תקין ומשווים את החיווים לחלק הנבדק.

סליל מוחלט יחיד (איור 2 א): סליל אחד משמש ליצירת שדה מגנטי וגם לגילוי השדה שנוצר על ידי זרמי מערבולת מושרים. מכיוון שבשיטה זו לא משתמשים ייחוס השיטה נקראת שיטה מוחלטת.

סליל מוחלט כפול (איור 2 ב): שני סלילים: האחד מייצר שדה מגנטי ומשרה זרמי מערבולת וסליל שני מחובר למערכת מדידה (ולא למקור מתח החילופין), בדרך כלל הסליל השני נמצא בתוך הסליל הראשון .



איור 3: סליל מוחלט יחיד (א) וסליל מוחלט כפול (ב)

סליל דיפרנציאלי: הסלילים שבציור 3א מלופפים כך שהפלט של סליל אחד מבטל את הפלט של הסליל השני כשתכונות החומר שבליבות שני הסלילים הן שוות. במילים אחרות, התופעות הזהות בשני הסלילים מאוזנות. הפרש קטן בתכונות החומר שבתוך שני הסלילים יגרום לאי איזון במעגל ולחיווי חשמלי על השינוי. אפשר להשתמש בשיטה זו בשתי דרכים:

השוואה עצמית: משתמשים בקטע אחד של החלק הנבדק כדגם יחוס (סטנדרט9 מול אזור אחר. מניחים שפגם שימצא בחלק לא יהיה מפושט על שני האזורים כך שיווצר הפרש בין שני האזורים (3ב).

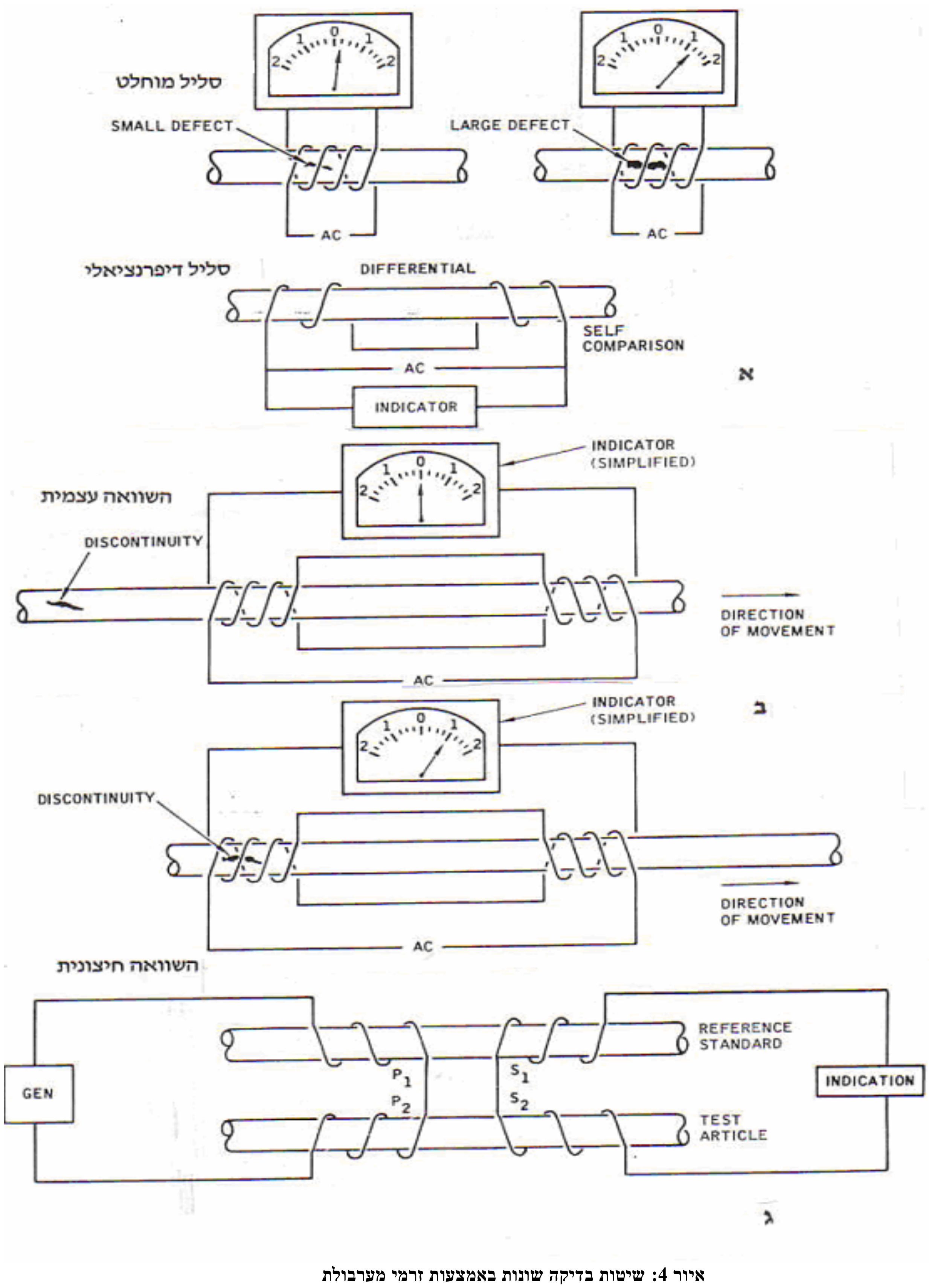
השוואה חיצונית: משתמשים בדגם ייחוס קבוע חופשי מפגמים ומשווים ברציפות את הזרם בדגם הייחוס לחלק הנבדק (או8 המיוצר בפס ייצור רציף). אם פגם עובר בסליל PI-SI הוא יגרום לשינוי באימפדנס שלו ולחיווי במערכת האלקטרונית (3ג).

7.2. את האות החשמלי המתקבל בסלילים אפשר לעבד בשלושה אופנים:

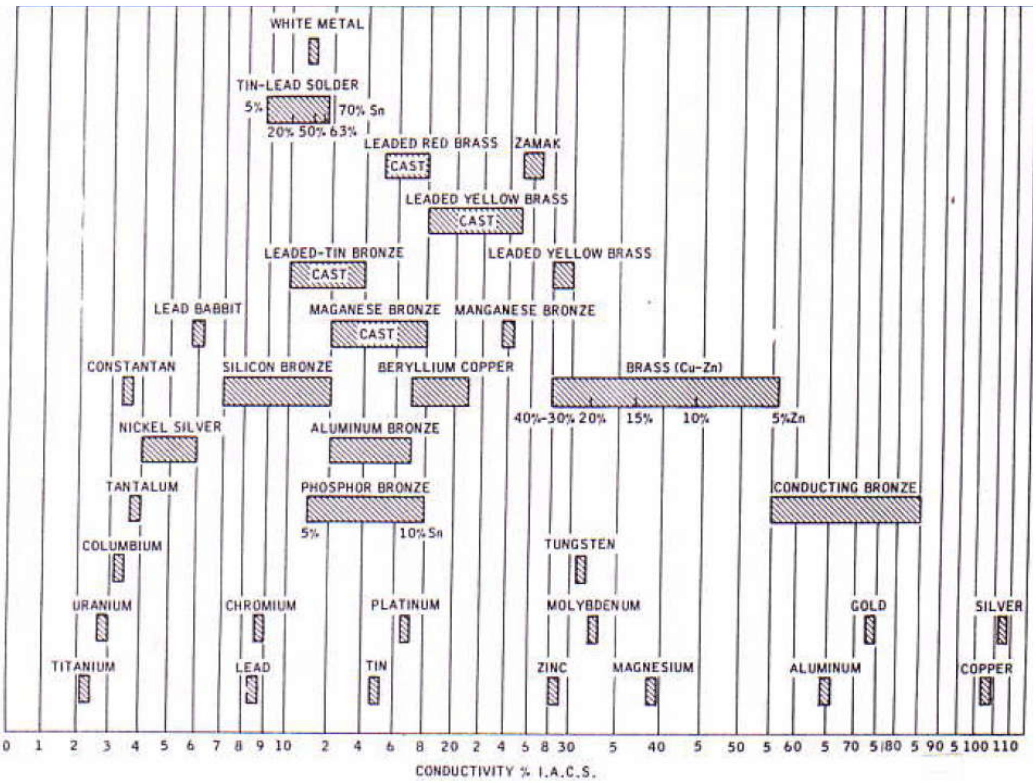
7.2.1. **מדידת אימפדנס:** השיטה הפשוטה ביותר. האימפדנס תלוי בכל שלושת הגורמים המשפיעים על זרמי המערבולת: אי רציפויות, מוליכות, ומידות החלק.

7.2.2. אנליזת פזה: ניתוח הפרש הפזה בין הזרם למתח בסליל הבוחן. הפרמביליות ומידות החלק משפיעים על זווית הפזה באותו כיוון. המוליכות החשמלית משפיעה בהבדל של 90° ולכן אפשר להבחין בין גורמים אלה.

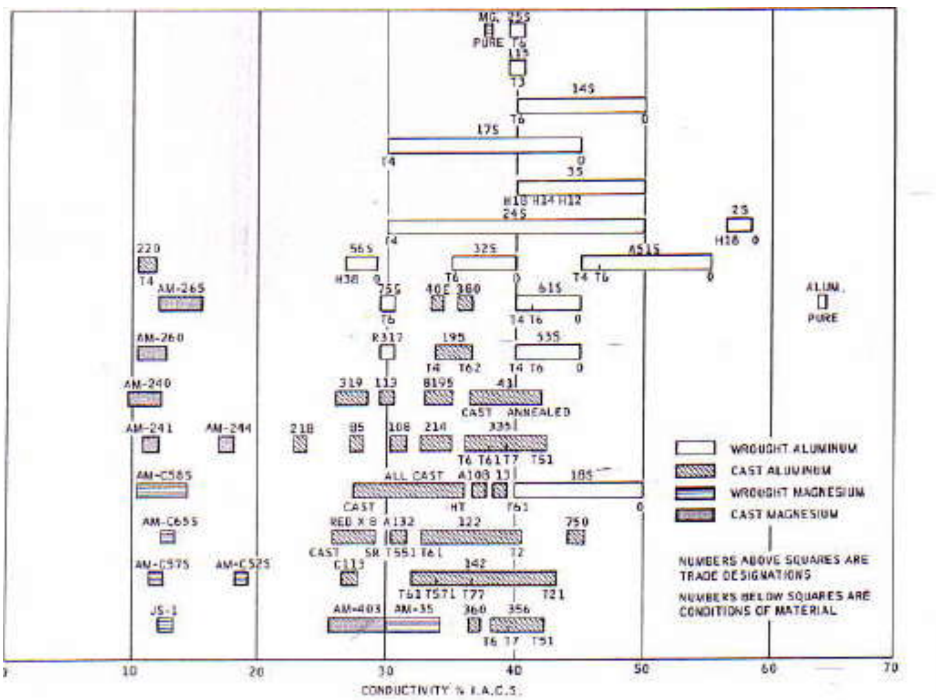
7.2.3. מודולציית תדר: מיושמת בביקורת איכות לזהות אזורים פגומים בפס ייצור רצוף.



איור 4: שיטות בדיקה שונות באמצעות זרמי מערבולת

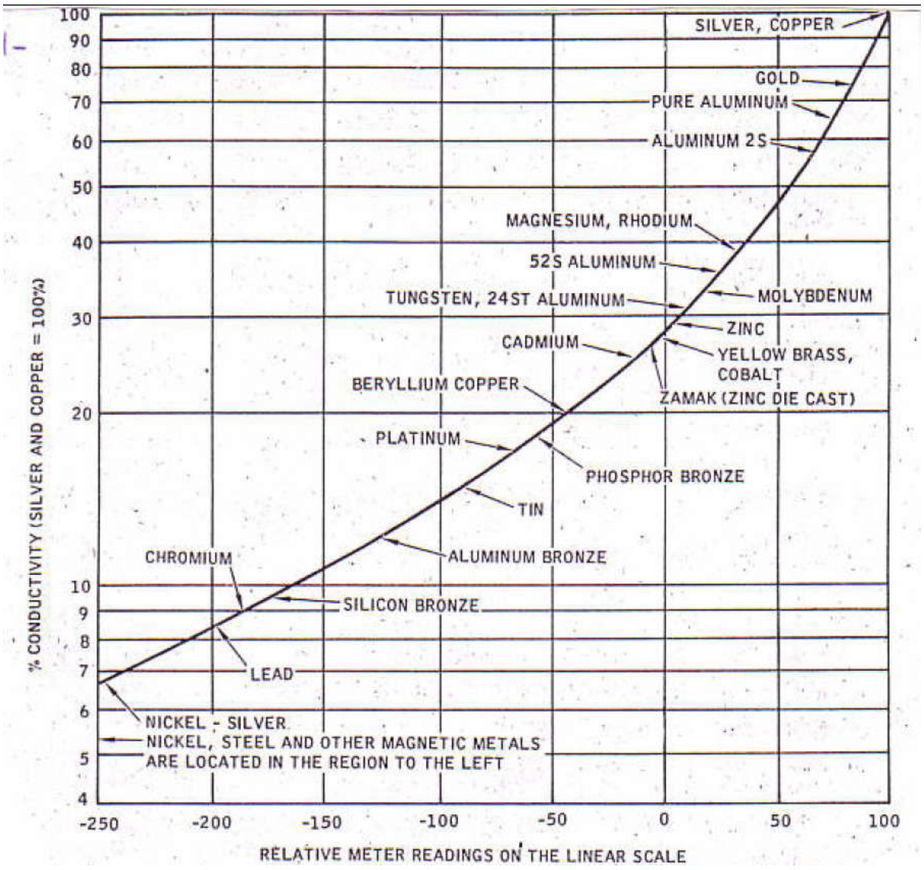


א

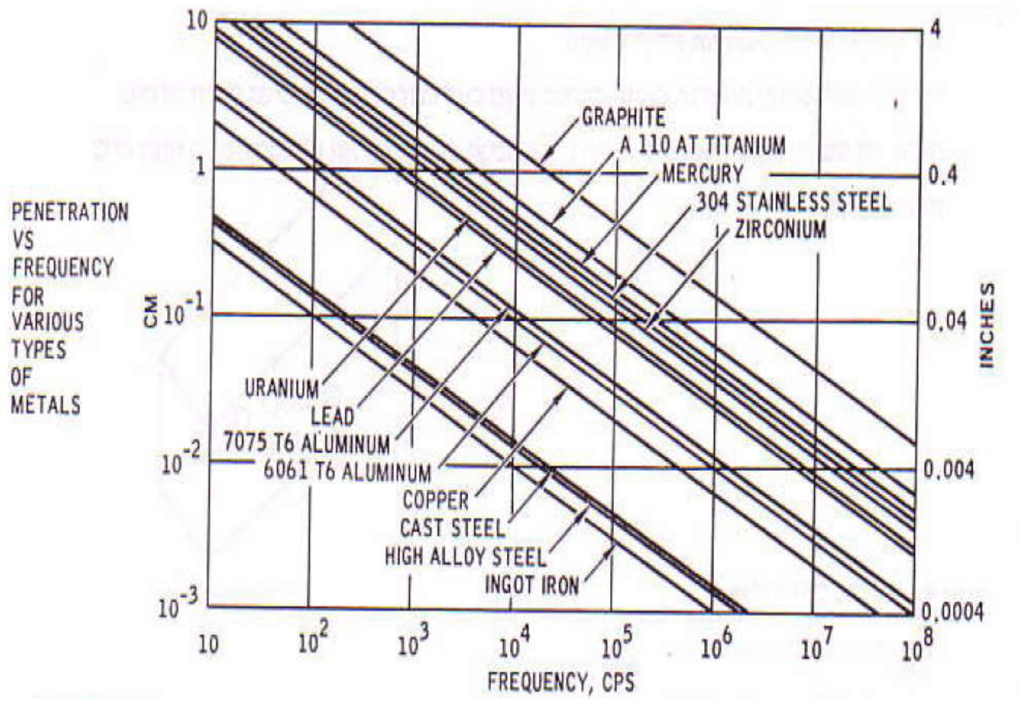


ב

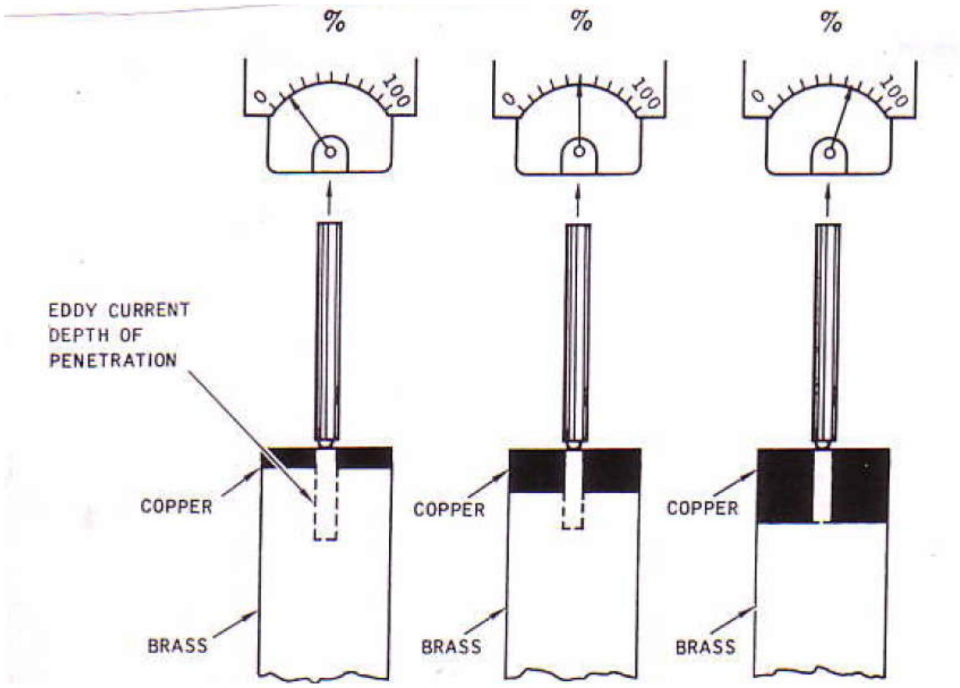
איור 5: מוליכות חשמלית של נתכים מתכתיים (ב) קנה מידה מוגדל של (א)



איור 6: מוליכות יחסית של נתכים שונים על פי תקן IACS כפונקציה של הקריאה הלינארית של מכשיר זרמי המערבולת



איור 7: תלות עומק החדירה של זרמי מערבולת בתדירות השדה המשרה למתכות שונות



איור 8: בדיקת ציפוי נחושת על פליז. החדירה עמוקה יותר כשעובי הנחושת קטן.

טבלה 1: מוליכות חשמלית וקושי של נתכי אלומיניום המחוזקים על ידי המסה וזיקון

ALUMINUM ALLOY - SHEET AND PLATE - BARE

MAT MAT'L	SPEC	COND.	STANDARD	SUPERFICIAL	BRINELL VALUE 10MM BALL 500 kg. LOAD	CONDUCTIVITY VALUE % OF IACS * ** (MATERIAL THICKNESS .050 & THICKER)
5456	MIL-A-19842	0 H321 H343	NO HARDNESS TEST DATA AVAILABLE NO HARDNESS TEST DATA AVAILABLE NO HARDNESS TEST DATA AVAILABLE			
6061	QQ-A-327	0 T4 T6, T651	H75 MAX. H91 MIN. E85 MIN.	 15T64 MIN. 30T47.5 MIN.	 57 MIN. 80 MIN.	44.0 - 49.0 35.5 - 40.5 40.0 - 45.0
7075	QQ-A-283 MMS-159	0 T6, T651 T73	E77 MAX. B83 MIN. B69 MIN.	30T38.5 MAX. 30T72 MIN. (SEE NOTE 1 AT BOTTOM OF PAGE)	70 MAX. 137 MIN.	44.0 - 47.0 30.5 - 34.5 38.0 MIN:
7079 7178	MIL-A-8877	T6, T651 0	NO HARDNESS TEST DATA AVAILABLE			30.5 - 34.0 43.0 - 47.0
7178 7079 7079	MIL-A-9180	T6, T651 0 T6, T652	B86 MIN.	30T74 MIN.	145 MIN.	30.0 - 34.0 44.0 - 47.0 30.5 - 34.0

NOTE 1: THIS VALUE IS TO BE USED ONLY TO DETERMINE THAT MATERIAL IS NOT IN THE "0" CONDITION. IT DOES NOT IN ANY WAY INDICATE WHETHER OR NOT THE MATERIAL HAS BEEN PROPERLY HEAT TREATED TO THE T73 CONDITION.

* NORMAL ROCKWELL TESTING WILL BE USED ON MATERIAL THICKNESSES OUTSIDE THE RANGES AUTHORIZED FOR CONDUCTIVITY TESTING.

** A ROCKWELL SAMPLE SHALL BE TAKEN FOR THOSE LOTS TESTED ENTIRELY BY CONDUCTIVITY TESTING.

טבלה 2: עומקי חדירה אופייניים של זרמי מערבולת

METAL	CONDUCTIVITY (% IACS)	RESISTIVITY MICROHM-CM	PERMEABILITY	37% DEPTH OF PENETRATION IN INCHES AT VARIOUS FREQUENCIES					
				1KC	4KC	16KC	64KC	256KC	1MC
COPPER	100	1.7	1	.082	.041	.021	.010	.005	.0026
6061-T6 ALUMINUM	42	4.1	1	.126	.063	.032	.016	.008	.0040
7075-T6 ALUMINUM	32	5.3	1	.144	.072	.036	.018	.009	.0046
MAGNESIUM	37	4.6	1	.134	.067	.034	.017	.008	.0042
LEAD	7.8	22	1	.292	.146	.073	.037	.018	.0092
URANIUM	6.0	29	1	.334	.167	.084	.042	.021	.0106
ZIRCONIUM	3.4	50	1	.446	.223	.112	.056	.028	.0141
304 STAINLESS STEEL	2.5	70	1.02	.516	.258	.129	.065	.032	.0164
HIGH ALLOY STEEL WITHOUT SATURATION*	2.9	60	750	.019	.0095	.0048	.0024	.0012	.0006
CAST STEEL WITHOUT SATURATION*	10.7	16	175	.018	.0089	.0044	.0022	.0011	.0006

*IF FERROMAGNETIC STEELS ARE TESTED USING SATURATION, THE DEPTH OF PENETRATION IS INCREASED TO APPROXIMATELY THAT NORMALLY FOUND IN STAINLESS STEEL.

חלק ג' - בדיקת חלקיקים מגנטיים

1. תקציר:

1. הכרת שיטת הבדיקה ללא הרס של מתכות פרומגנטיות באמצעות חלקיקים מגנטיים.
2. הכרת הציוד המשמש לביצוע הבדיקה.
3. שימוש בשיטה לזיהוי פגמים בחומר.

*נלקח מאתר האינטרנט
http://www.ndt-ed.org/EducationResources/CommunityCollege/communitycollege.htm

2. רקע תיאורטי *

2.12. Introduction

Magnetic particle inspection (MPI) is a nondestructive testing method used for defect detection. MPI is fast and relatively easy to apply, and part surface preparation is not as critical as it is for some other NDT methods. These characteristics make MPI one of the most widely utilized nondestructive testing methods. MPI uses magnetic fields and small magnetic particles (i.e.iron filings) to detect flaws in components. The only requirement from an inspectability standpoint is that the component being inspected must be made of a ferromagnetic material such as iron, nickel, cobalt, or some of their alloys. Ferromagnetic materials are materials that can be magnetized to a level that will allow the inspection to be effective. The method is used to inspect a variety of product forms including castings, forgings, and weldments. Many different industries use magnetic particle inspection for determining a component's fitness-for-use. Some examples of industries that use magnetic particle inspection are the structural steel, automotive, petrochemical, power generation, and aerospace industries. Underwater inspection is another area where magnetic particle inspection may be used to test items such as offshore structures and underwater pipeline.

2.13. Basic Principles

In theory, magnetic particle inspection (MPI) is a relatively simple concept. It can be considered as a combination of two nondestructive testing methods: magnetic flux leakage testing and visual testing.

Consider the case of a bar magnet (figure 1). It has a magnetic field in and around the magnet.

Any place that a magnetic line of force exits or enters the magnet is called a pole. A pole where a magnetic line of force exits the magnet is called a north pole and a pole where a line of force enters the magnet is called a south pole.

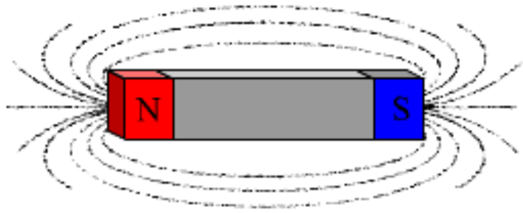


figure 1: a bar magnet

When a bar magnet is broken in the center of its length (figure 2), two complete bar magnets with magnetic poles on each end of each piece will result. If the magnet is just cracked but not broken completely in two, a north and south pole will form at each edge of the crack. The magnetic field exits the north pole and reenters at the south pole. The magnetic field spreads out when it encounters the small air gap created by the crack because the air cannot support as much magnetic field per unit volume as the magnet can. When the field spreads out, it appears to leak out of the material and, thus is called a flux leakage field.

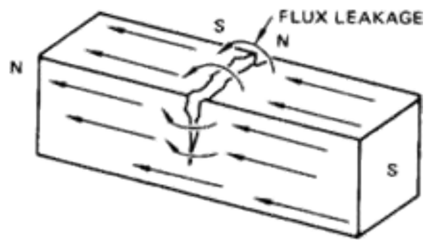


figure 2: a bar magnet broken in the center

If iron particles are sprinkled on a cracked magnet (figure 3) , the particles will be attracted to and cluster not only at the poles at the ends of the magnet, but also at the poles at the edges of the crack. This cluster of particles is much easier to see than the actual crack and this is the basis for magnetic particle inspection.

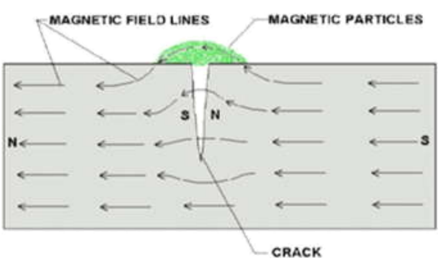


figure 3: iron particles are sprinkled on a cracked magnet

The first step in a magnetic particle inspection is to magnetize the component that is to be inspected. If any defects on or near the surface are present, the defects will create a leakage field. After the component has been magnetized, iron particles, either in a dry or wet suspended form, are applied to the surface of the magnetized part. The particles will be attracted and cluster at the flux leakage fields, thus forming a visible indication that the inspector can detect.

2.14. Diamagnetic, Paramagnetic, and Ferromagnetic Materials

When a material is placed within a magnetic field, the magnetic forces of the material's electrons will be affected. This effect is known as Faraday's Law of Magnetic Induction. However, materials can react quite differently to the presence of an external magnetic field. This reaction is dependent on a number of factors, such as the atomic and molecular structure of the material, and the net magnetic field associated with the atoms. The magnetic moments associated with atoms have three origins. These are the electron orbital motion, the change in orbital motion caused by an external magnetic field, and the spin of the electrons. In most atoms, electrons occur in pairs. Electrons in a pair spin in opposite directions. So, when electrons are paired together, their opposite spins cause their magnetic fields to cancel each other. Therefore, no net magnetic field exists. Alternately, materials with some unpaired electrons will have a net magnetic field and will react more to an external field. Most materials can be classified as diamagnetic, paramagnetic or ferromagnetic.

2.14.1. Diamagnetic metals

have a very weak and negative susceptibility to magnetic fields. Diamagnetic materials are slightly repelled by a magnetic field and the material does not retain the magnetic properties when the external field is removed. Diamagnetic materials are solids with all paired electron resulting in no permanent net magnetic moment per atom. Diamagnetic properties arise from the realignment of the electron orbits under the influence of an external magnetic field. Most elements in the periodic table, including copper, silver, and gold, are diamagnetic.

2.14.2. Paramagnetic metals

have a small and positive susceptibility to magnetic fields. These materials are slightly attracted by a magnetic field and the material does not retain the magnetic properties when the external field is removed. Paramagnetic properties are due to the presence of some unpaired electrons, and from the realignment of the electron orbits caused by the external magnetic field. Paramagnetic materials include magnesium, molybdenum, lithium, and tantalum.

2.14.3. Ferromagnetic materials

have a large and positive susceptibility to an external magnetic field. They exhibit a strong attraction to magnetic fields and are able to retain their magnetic properties after the external field has been removed. Ferromagnetic materials have some unpaired electrons so their atoms have a net magnetic moment. They get their strong magnetic properties due to the presence of magnetic domains. In these domains, large numbers of atom's moments (10^{12} to 10^{15}) are aligned parallel so that the magnetic force within the domain is strong. When a ferromagnetic material is in the unmagnitized state, the domains are nearly randomly organized and the net magnetic field for the part as a whole is zero. When a magnetizing force is applied, the domains become aligned to produce a strong magnetic field within the part. Iron, nickel, and cobalt are examples of ferromagnetic materials. Components with these materials are commonly inspected using the magnetic particle method.

2.15. Magnetic Domains

Ferromagnetic materials get their magnetic properties not only because their atoms carry a magnetic moment but also because the material is made up of small regions known as magnetic domains. In each domain, all of the atomic dipoles are coupled together in a preferential direction. This alignment develops as the material develops its crystalline structure during solidification from the molten state. Magnetic domains can be detected using Magnetic Force Microscopy (MFM) and images of the domains like the one shown below (figure 4) can be constructed.

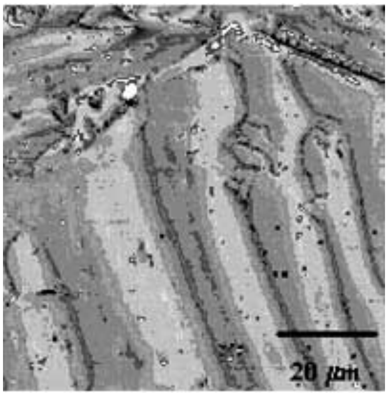


figure 4: Magnetic Force Microscopy (MFM) image showing the magnetic domains in a piece of heat treated carbon steel.

During solidification, a trillion or more atom moments are aligned parallel so that the magnetic force within the domain is strong in one direction. Ferromagnetic materials are said to be characterized by "spontaneous magnetization" since they obtain saturation magnetization in each of the domains without an external magnetic field being applied. Even though the domains are magnetically saturated, the bulk material may not show any signs of magnetism because the domains develop themselves and are randomly oriented relative to each other (figure 5). Ferromagnetic materials become magnetized when the magnetic domains within the material are aligned (figure 6). This can be done by placing the material in a strong external magnetic field or by passing electrical current through the material. Some or all of the domains can become aligned. The more domains that are aligned, the stronger the magnetic field in the material. When all of the domains are aligned, the material is said to be magnetically saturated. When a material is magnetically saturated, no additional amount of external magnetization force will cause an increase in its internal level of magnetization.

figure 5: the domains are randomly oriented relative to each othe

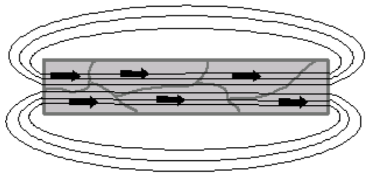


figure 6: the magnetic domains within the material are aligned

2.16. Magnetic Field In and Around a Bar Magnet

As discussed previously, a magnetic field is a change in energy within a volume of space. The magnetic field surrounding a bar magnet can be seen in the magnetograph below (figure 7). A magnetograph can be created by placing a piece of paper over a magnet and sprinkling the paper with iron filings. The particles align themselves with the lines of magnetic force produced by the magnet. The magnetic lines of force show where the magnetic field exits the material at one pole and reenters the material at another pole along the length of the magnet. It should be noted that the magnetic lines of force exist in three dimensions but are only seen in two dimensions in the image.

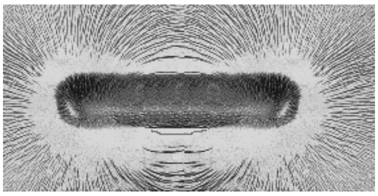


figure 7: The magnetic field surrounding a bar magnet

It can be seen in the magnetograph that there are poles all along the length of the magnet but that the poles are concentrated at the ends of the magnet. The area where the exit poles are concentrated is called the magnet's north pole and the area where the entrance poles are concentrated is called the magnet's south pole.

2.17. Magnetic Fields in and around Horseshoe and Ring Magnets

Magnets come in a variety of shapes and one of the more common is the horseshoe (U) magnet. The horseshoe magnet has north and south poles just like a bar magnet but the magnet is curved so the poles lie in the same plane (figure 8). The magnetic lines of force flow from pole to pole just like in the bar magnet. However, since the poles are located closer together and a more direct path exists for the lines of flux to travel between the poles, the magnetic field is concentrated between the poles.

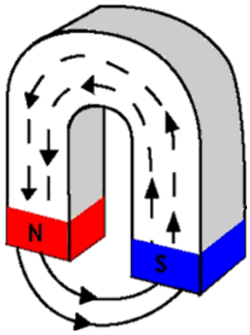


figure 8: The horseshoe magnet

If a bar magnet was placed across the end of a horseshoe magnet (figure 9) or if a magnet was formed in the shape of a ring, the lines of magnetic force would not even need to enter the air. The value of such a magnet where the magnetic field is completely contained with the material probably has limited use. However, it is important to understand that the magnetic field can flow in loop within a material.

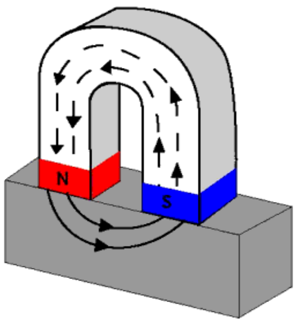


figure 9: a bar magnet placed across the end of a horseshoe magnet

2.18. General Properties of Magnetic Lines of Force

Magnetic lines of force (figure 10) have a number of important properties, which include:

- They seek the path of least resistance between opposite magnetic poles. In a single bar magnet as shown to the right, they attempt to form closed loops from pole to pole.
- They never cross one another.
- They all have the same strength.
- Their density decreases (they spread out) when they move from an area of higher permeability to an area of lower permeability.
- Their density decreases with increasing distance from the poles.

- They are considered to have direction as if flowing, though no actual movement occurs.
- They flow from the south pole to the north pole within a material and north pole to south pole in air.

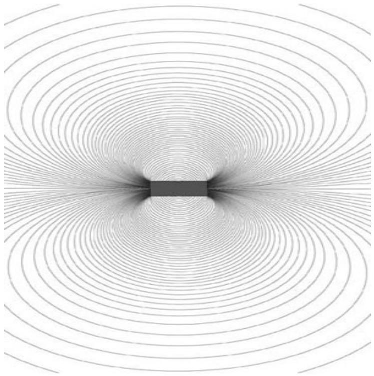


figure 10: Magnetic lines of force

2.19. Electromagnetic Fields

Magnets are not the only source of magnetic fields. In 1820, Hans Christian Oersted discovered that an electric current flowing through a wire caused a nearby compass to deflect. This indicated that the current in the wire was generating a magnetic field. Oersted studied the nature of the magnetic field around the long straight wire. He found that the magnetic field existed in circular form around the wire (figure 11) and that the intensity of the field was directly proportional to the amount of current carried by the wire. He also found that the strength of the field was strongest next to the wire and diminished with distance from the conductor until it could no longer be detected. In most conductors, the magnetic field exists only as long as the current is flowing (i.e. an electrical charge is in motion). However, in ferromagnetic materials the electric current will cause some or all of the magnetic domains to align and a residual magnetic field will remain.

figure 11: magnetic field around a long straight wire

Oersted also noticed that the direction of the magnetic field was dependent on the direction of the electrical current in the wire. A three-dimensional representation of the magnetic field is shown below. There is a simple rule for remembering the direction of the magnetic field around a conductor. It is called the **right-hand rule**. If a person grasps a conductor in one's right hand with the thumb pointing in the direction of the current, the fingers will circle the conductor in the direction of the magnetic field (figure 12).

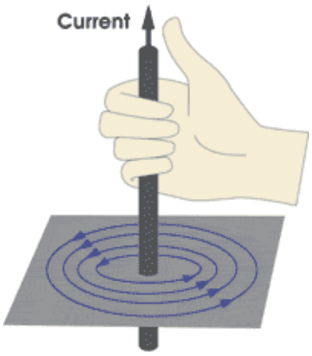


figure 12: the right-hand rule

2.20. Magnetic Field Produced by a Coil

When a current carrying conductor is formed into a loop or several loops to form a coil, a magnetic field develops that flows through the center of the loop or coil along its longitudinal axis and circles back around the outside of the loop or coil (figure 13). The magnetic field circling each loop of wire combines with the fields from the other loops to produce a concentrated field down the center of the coil. A loosely wound coil is illustrated below to show the interaction of the magnetic field. The magnetic field is essentially uniform down the length of the coil when it is wound tighter.

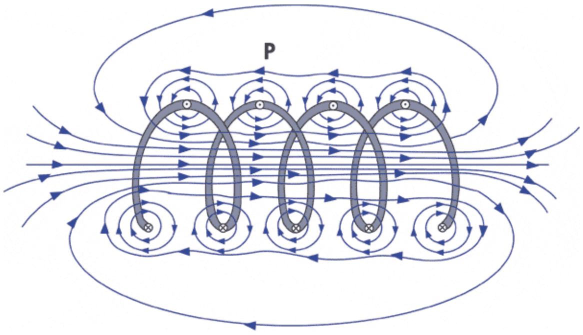


figure 13: Magnetic Field Produced by a Coil

The strength of a coil's magnetic field increases not only with increasing current but also with each loop that is added to the coil. A long, straight coil of wire is called a solenoid and can be used to generate a nearly uniform magnetic field similar to that of a bar magnet. The concentrated magnetic field inside a coil is very useful in magnetizing ferromagnetic materials for inspection using the magnetic particle testing method. Please be aware that the field outside the coil is weak and is not suitable for magnetizing ferromagnetic materials.

2.21. The Hysteresis Loop and Magnetic Properties

A great deal of information can be learned about the magnetic properties of a material by studying its hysteresis loop (figure 14). A hysteresis loop shows the relationship between the induced magnetic flux density **(B)** and the magnetizing force **(H).** It is often referred to as the B-H loop. An example hysteresis loop is shown below.

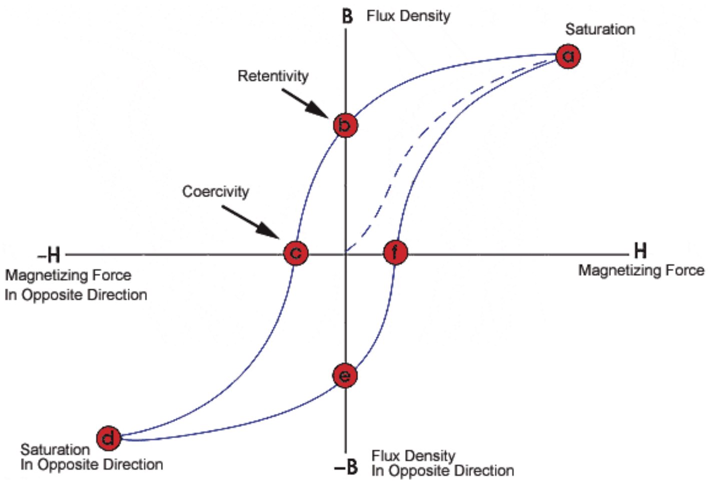


figure 14: The Hysteresis Loop

The loop is generated by measuring the magnetic flux of a ferromagnetic material while the magnetizing force is changed. A ferromagnetic material that has never been previously magnetized or has been thoroughly demagnetized will follow the dashed line as **H** is increased. As the line demonstrates, the greater the amount of current applied **(H+)**, the stronger the magnetic field in the component **(B+)**. At point "a" almost all of the magnetic domains are aligned and an additional increase in the magnetizing force will produce very little increase in magnetic flux. The material has reached the point of magnetic saturation. When **H** is reduced to zero, the curve will move from point "a" to point "b." At this point, it can be seen that some magnetic flux remains in the material even though the magnetizing force is zero. This is referred to as the point of retentivity on the graph and indicates the remanence or level of residual magnetism in the material. (Some of the magnetic domains remain aligned but some have lost their alignment.) As the magnetizing force is reversed, the curve moves to point "c", where the flux has been reduced to zero. This is called the point of coercivity on the curve. (The reversed magnetizing force has flipped enough of the domains so that the net flux within the material is zero.) The force required to remove the residual magnetism from the material is called the coercive force or coercivity of the material. As the magnetizing force is increased in the negative direction, the material will again become magnetically saturated but in the opposite direction (point "d"). Reducing **H** to zero brings the curve to point "e." It will have a level of residual magnetism equal to that achieved in the other direction. Increasing **H** back in the positive direction will return **B** to zero. Notice that the curve did not return to the origin of the graph because some force is required to remove the residual magnetism. The curve will take a different path from point "f" back to the saturation point where it with complete the loop.
From the hysteresis loop, a number of primary magnetic properties of a material can be determined:

2.21.1. Retentivity - A measure of the residual flux density corresponding to the saturation induction of a magnetic material. In other words, it is a material's ability to retain a certain amount of residual magnetic field when the magnetizing force is removed after achieving saturation. (The value of **B** at point b on the hysteresis curve.)

2.21.2. Residual Magnetism or **Residual Flux** - the magnetic flux density that remains in a material when the magnetizing force is zero. Note that residual magnetism and retentivity are the same when the material has been magnetized to the saturation point. However, the level of residual magnetism may be lower than the retentivity value when the magnetizing force did not reach the saturation level.

2.21.3. Coercive Force - The amount of reverse magnetic field which must be applied to a magnetic material to make the magnetic flux return to zero. (The value of **H** at point c on the hysteresis curve.)

2.21.4. Permeability, □- A property of a material that describes the ease with which a magnetic flux is established in the component.

2.21.5. Reluctance - Is the opposition that a ferromagnetic material shows to the establishment of a magnetic field. Reluctance is analogous to the resistance in an electrical circuit.

2.22. Permeability

As previously mentioned, permeability is a material property that describes the ease with which a magnetic flux is established in a component. It is the ratio of the flux density to the magnetizing force and is represented by the following equation:

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

It is clear that this equation describes the slope of the curve at any point on the hysteresis loop (figure 15). The permeability value given in papers and reference materials is usually the maximum permeability or the maximum relative permeability. The maximum permeability is the point where the slope of the B/H curve for the unmagnetized material is the greatest. This point is often taken as the point where a straight line from the origin is tangent to the B/H curve.

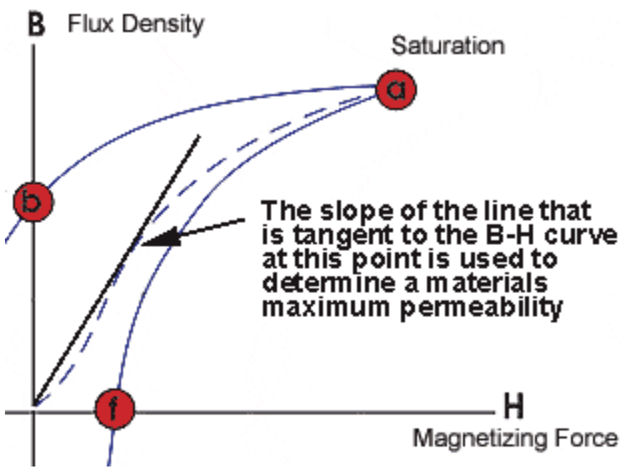


figure 15: the slope of the curve on the hysteresis loop.

The relative permeability is arrived at by taking the ratio of the material's permeability to the permeability in free space (air).

μ(relative) = μ (material) / μ air

where: μ air = 1.256 x 10^{-6} H/m

The shape of the hysteresis loop tells a great deal about the material being magnetized. The hysteresis curves of two different materials are shown in the graph.

Relative to other materials, a material with a wider hysteresis loop has:

- Lower Permeability
- Higher Retentivity
- Higher Coercivity
- Higher Reluctance
- Higher Residual Magnetism

Relative to other materials, a material with the narrower hysteresis loop has:

- Higher Permeability
- Lower Retentivity
- Lower Coercivity
- Lower Reluctance
- Lower Residual Magnetism

In magnetic particle testing, the level of residual magnetism is important. Residual magnetic fields are affected by the permeability, which can be related to the carbon content and alloying of the material. A component with high carbon content will have low permeability and will retain more magnetic flux than a material with low carbon content.

2.23. Magnetic Field Orientation and Flaw Detectability

To properly inspect a component for cracks or other defects, it is important to understand that the orientation between the magnetic lines of force and the flaw is very important. There are two general types of magnetic fields that can be established within a component. A longitudinal magnetic field has magnetic lines of force that run parallel to the long axis of the part (figure 16). Longitudinal magnetization of a component can be accomplished using the longitudinal field set up by a coil or solenoid. It can also be accomplished using permanent magnets or electromagnets. A circular magnetic field (figure 17) has magnetic lines of force that run circumferentially around the perimeter of a part. A circular magnetic field is induced in an article by either passing current through the component or by passing current through a conductor surrounded by the component.

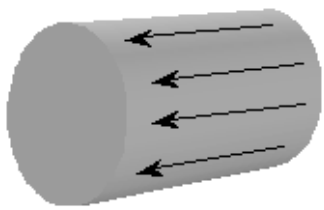


figure 16: A longitudinal magnetic field

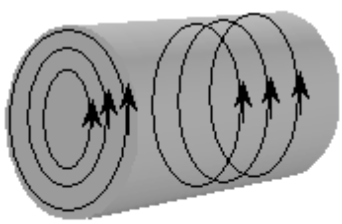


figure 17: A circular magnetic field

The type of magnetic field established is determined by the method used to magnetize the specimen. Being able to magnetize the part in two directions is important because the best detection of defects occurs when the lines of magnetic force are established at right angles to the longest dimension of the defect. This orientation creates the largest disruption of the magnetic field within the part and the greatest flux leakage at the surface of the part. As can be seen in the image below, if the magnetic field is parallel to the defect, the field will see little disruption and no flux leakage field will be produced.

An orientation of 45 to 90 degrees between the magnetic field and the defect is necessary to form an indication (figure 18). Since defects may occur in various and unknown directions, each part is normally magnetized in two directions at right angles to each other. If the component below is considered, it is known that passing current through the part from end to end will establish a circular magnetic field that will be 90 degrees to the direction of the current. Therefore, defects that have a significant dimension in the direction of the current (longitudinal defects) should be detectable. Alternately, transverse-type defects will not be detectable with circular magnetization.

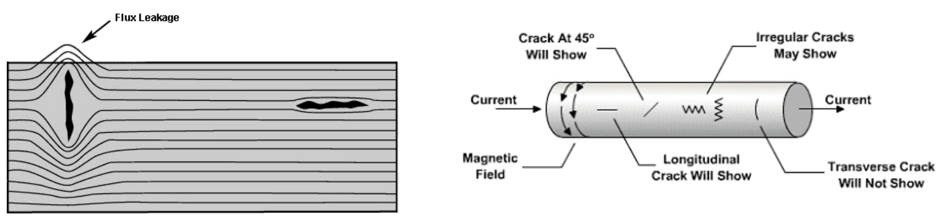


figure 68: An orientation of 45 to 90 degrees between the magnetic field and the defect is necessary to form an indication

2.24. Magnetization of Ferromagnetic Materials

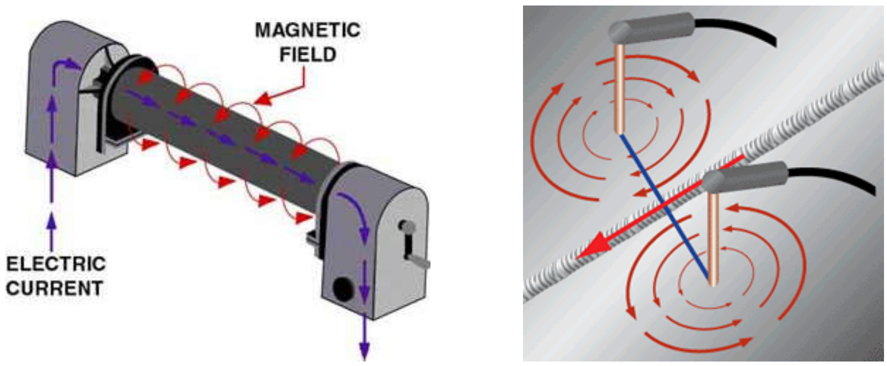
There are a variety of methods that can be used to establish a magnetic field in a component for evaluation using magnetic particle inspection. It is common to classify the magnetizing methods as either direct or indirect

2.24.1. Magnetization Using Direct Induction (Direct Magnetization)

With direct magnetization, current is passed directly through the component. Recall that whenever current flows, a magnetic field is produced. Using the right-hand rule, which was introduced earlier, it is known that the magnetic lines of flux form normal to the direction of the current and form a circular field in and around the conductor. When using the direct magnetization method, care must be taken to ensure that good electrical contact is established and maintained between the test equipment and the test component. Improper contact can result in arcing that may damage the component. It is also possible to overheat components in areas of high resistance such as the contact points and in areas of small cross-sectional area.

There are several ways that direct magnetization is commonly accomplished. One way involves clamping the component between two electrical contacts in a special piece of equipment (figure 19a). Current is passed through the component and a circular magnetic field is established in and around the component. When the magnetizing current is stopped, a residual magnetic field will remain within the component. The strength of the induced magnetic field is proportional to the amount of current passed through the component.

second technique involves using clamps or prods, which are attached or placed in contact with the component (figure 19b). Electrical current flows through the component from contact to contact. The current sets up a circular magnetic field around the path of the current.



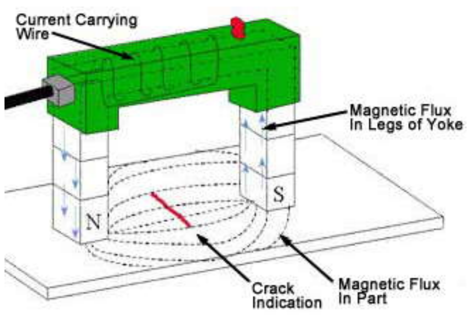
(a) (b)

figure 19: direct magnetization: electrical contacts(a), clamps or prods(b)

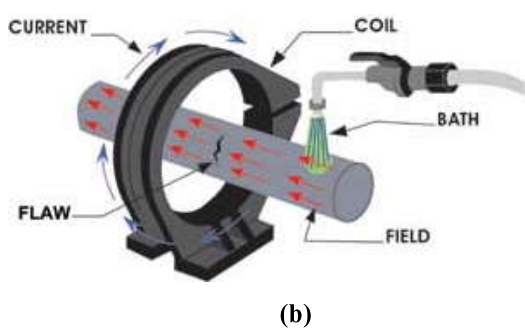
2.24.2. Magnetization Using Indirect Induction (Indirect Magnetization)

Indirect magnetization is accomplished by using a strong external magnetic field to establish a magnetic field within the component. As with direct magnetization, there are several ways that indirect magnetization can be accomplished.
The use of **permanent magnets** is a low cost method of establishing a magnetic field. However, their use is limited due to lack of control of the field strength and the difficulty of placing and removing strong permanent magnets from the component. **Electromagnets** in the form of an adjustable horseshoe magnet (called a yoke)(figure 20a) eliminate the problems associated with permanent magnets and are used extensively in industry. Electromagnets only exhibit a magnetic flux when electric current is flowing around the soft iron core. When the magnet is placed on the component, a magnetic field is established between the north and south poles of the magnet.

Another way of indirectly inducting a magnetic field in a material is by using the magnetic field of a current carrying conductor. A circular magnetic field can be established in cylindrical components by using a **central conductor.** Typically, one or more cylindrical components are hung from a solid copper bar running through the inside diameter. Current is passed through the copper bar and the resulting circular magnetic field establishes a magnetic field within the test components.
The use of **coils** and **solenoids** is a third method of indirect magnetization (figure 20b). When the length of a component is several times larger than its diameter, a longitudinal magnetic field can be established in the component. The component is placed longitudinally in the concentrated magnetic field that fills the center of a coil or solenoid. This magnetization technique is often referred to as a "coil shot."



(a)



(b)

Figure 20: Indirect magnetization: horseshoe magnet (a yoke) (a), coils and solenoids(b)

2.25. Magnetizing Current

As seen in the previous pages, electric current is often used to establish the magnetic field in components during magnetic particle inspection. Alternating current and direct current are the two basic types of current commonly used. Current from single phase 110 volts, to three phase 440 volts, are used when generating an electric field in a component. Current flow is often modified to provide the appropriate field within the part. The type of current used can have an effect on the inspection results, so the types of currents commonly used will be briefly reviewed.

2.25.1. Direct Current

Direct current (DC) flows continuously in one direction at a constant voltage. A battery is the most common source of direct current. As previously mentioned, current is said to flow from the positive to the negative terminal. In actuality, the electrons flow in the opposite direction. DC is very desirable when inspecting for subsurface defects because DC generates a magnetic field that penetrates deeper into the material. In ferromagnetic materials, the magnetic field produced by DC generally penetrates the entire cross-section of the component. Conversely, the field produced using alternating current is concentrated in a thin layer at the surface of the component.

2.25.2. Alternating Current

Alternating current (AC) reverses in direction at a rate of 50 or 60 cycles per second. In the United States, 60 cycle current is the commercial norm but 50 cycle current is common in many countries. Since AC is readily available in most facilities, it is convenient to make use of it for magnetic particle inspection. However, when AC is used to induce a magnetic field in ferromagnetic materials, the magnetic field will be limited to narrow region at the surface of the component. This phenomenon is known as the "skin effect" and occurs because induction is not a spontaneous reaction and the rapidly reversing current does not allow the domains below the surface time to align.

Therefore, it is recommended that AC be used only when the inspection is limited to surface defects.

2.25.3. Rectified Alternating Current

Clearly, the skin effect limits the use of AC since many inspection applications call for the detection of subsurface defects. However, the convenient access to AC, drives its use beyond surface flaw inspections. Luckily, AC can be converted to current that is very much like DC through the process of rectification. With the use of rectifiers, the reversing AC can be converted to a one directional current. The three commonly used types of rectified current are described below.

2.26. Longitudinal Magnetic Fields Distribution and

2.26.1. Intensity

When the length of a component is several times larger than its diameter, a longitudinal magnetic field can be established in the component (figure 21). The component is often placed longitudinally in the concentrated magnetic field that fills the center of a coil or solenoid. This magnetization technique is often referred to as a "coil shot."

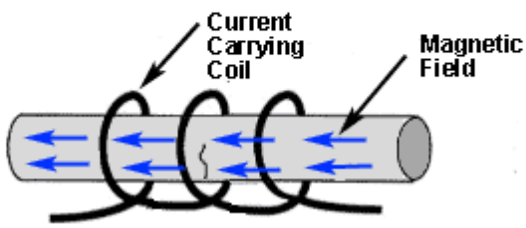


figure 71: a "coil shot"

The magnetic field travels through the component from end to end with some flux loss along its length as shown in the image to the right. Keep in mind that the magnetic lines of flux occur in three dimensions and are only shown in 2D in the image. The magnetic lines of flux (figure 22) are much denser inside the ferromagnetic material than in air because ferromagnetic materials have much higher permeability than does air. When the concentrated flux within the material comes to the air at the end of the component, it must spread out since the air can not support as many lines of flux per unit volume. To keep from crossing as they spread out, some of the magnetic lines of flux are forced out the side of the component.

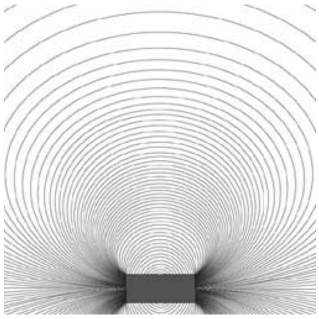


figure 22: The magnetic lines of flux

When a component is magnetized along its complete length, the flux loss is small along its length. Therefore, when a component is uniform in cross section and magnetic permeability, the flux density will be relatively uniform throughout the component. Flaws that run normal to the magnetic lines of flux will disturb the flux lines and often cause a leakage field at the surface of the component (figure 23).

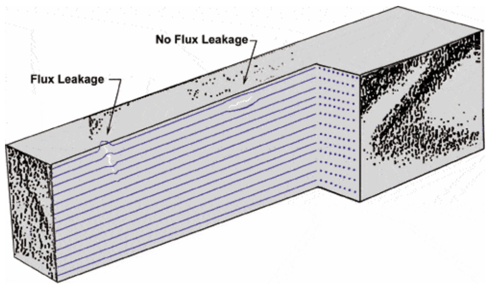


figure 23: a component magnetized along its complete length

When a component with considerable length is magnetized using a solenoid, it is possible to magnetize only a portion of the component (figure 24). Only the material within the solenoid and about the same width on each side of the solenoid will be strongly magnetized. At some distance from the solenoid, the magnetic lines of force will abandon their longitudinal direction, leave the part at a pole on one side of the solenoid and return to the part at a opposite pole on the other side of the solenoid. This occurs because the magnetizing force diminishes with increasing distance from the solenoid. As a result, the magnetizing force may only be strong enough to align the magnetic domains within and very near the solenoid. The unmagnetized portion of the component will not support as much magnetic flux as the magnetized portion and some of the flux will be forced out of the part as illustrated in the image below. Therefore, a long component must be magnetized and inspected at several locations along its length for complete inspection coverage.

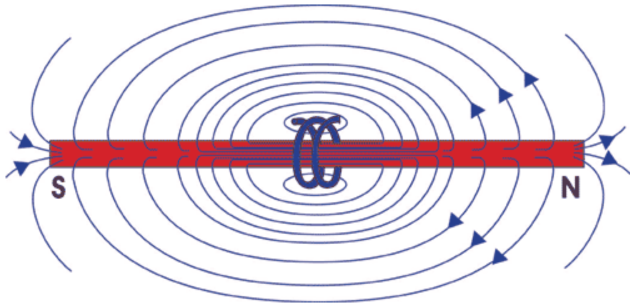


figure 24: a component with considerable length magnetized using a solenoid.

2.26.2. Circular Magnetic Fields Distribution and Intensity

As discussed previously, when current is passed through a solid conductor, a magnetic field forms in and around the conductor. The following statements can be made about the distribution and intensity of the magnetic field.

- The field strength varies from zero at the center of the component to a maximum at the surface.
- The field strength at the surface of the conductor decreases as the radius of the conductor increases when the current strength is held constant. (However, a larger conductor is capable of carrying more current.)
- The field strength outside the conductor is directly proportional to the current strength. Inside the conductor, the field strength is dependent on the current strength, magnetic permeability of the material, and if magnetic, the location on the B-H curve.
- The field strength outside the conductor decreases with distance from the conductor.

In the images below (figure 25), the magnetic field strength is graphed versus distance from the center of the conductor. It can be seen that in a nonmagnetic conductor carrying DC, the internal field strength rises from zero at the center to a maximum value at the surface of the conductor. The external field strength decrease with distance from the surface of the conductor. When the conductor is a magnetic material, the field strength within the conductor is much greater than it was in the nonmagnetic conductor (figure 26). This is due to the permeability of the magnetic material. The external field is exactly the same for the two materials provided the current level and conductor radius are the same.

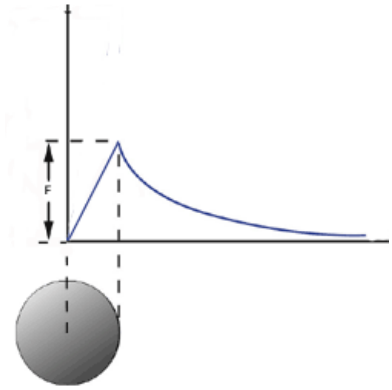


figure 25: The magnetic field distribution in and around a solid conductor of a nonmagnetic material carrying direct current.

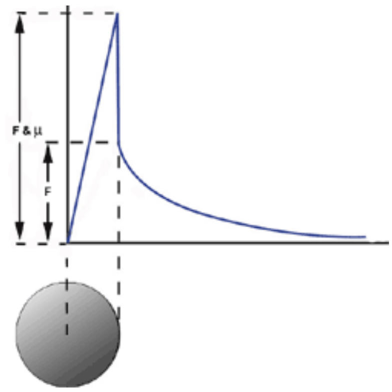


Figure 26: The magnetic field distribution in and around a solid conductor of a magnetic material carrying direct current.

When the conductor is carrying alternating current, the internal magnetic field strength rises from zero at the center to a maximum at the surface (figure 27). However, the field is concentrated in a thin layer near the surface of the conductor . This is known as the "skin effect." The skin effect is evident in the field strength versus distance graph for a magnetic conductor shown to the right. The external field decreases with increasing distance from the surface as it does with DC. It should be remembered that with AC the field is constantly varying in strength and direction.

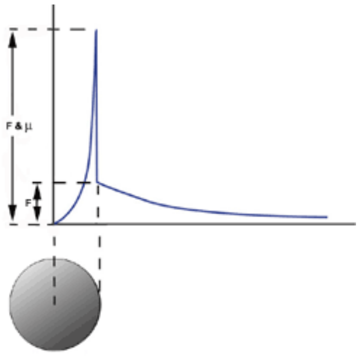


figure 27: The magnetic field distribution in and around a solid conductor of a magnetic material carrying alternating current.

In a hollow circular conductor there is no magnetic field in the void area. The magnetic field is zero at the inside wall surface and rises until it reaches a maximum at the outside wall surface (figure 28). As with a solid conductor, when the conductor is a magnetic material, the field strength within the conductor is much greater than it was in the nonmagnetic conductor due to the permeability of the magnetic material (figure 29). The external field strength decreases with distance from the surface of the conductor. The external field is exactly the same for the two materials provided the current level and conductor radius are the same.

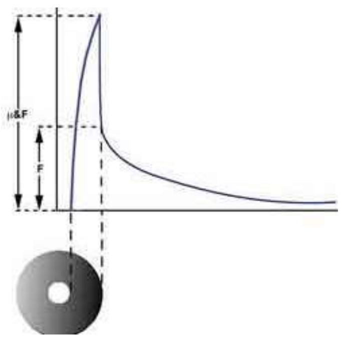


figure 28: The magnetic field distribution in and around a hollow conductor of a magnetic material carrying direct current.

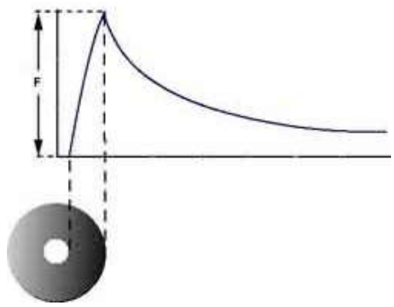


Figure 29: The magnetic field distribution in and around a hollow conductor of a nonmagnetic material carrying direct current

When AC is passed through a hollow circular conductor, the skin effect concentrates the magnetic field at the outside diameter of the component (figure 30).

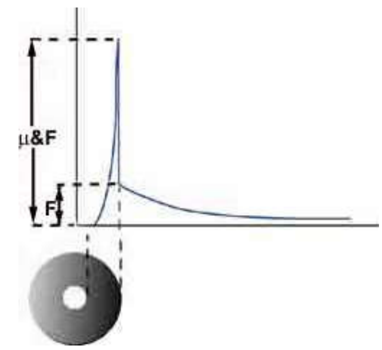


figure 80: The magnetic field distribution in and around a hollow conductor of a magnetic material carrying alternating current

2.26.3. Demagnetization

After conducting a magnetic particle inspection, it is usually necessary to demagnetize the component. Remanent magnetic fields can:

1. affect machining by causing cuttings to cling to a component.
2. interfere with electronic equipment such as a compass.
3. create a condition known as "arc blow" in the welding process. Arc blow may cause the weld arc to wonder or filler metal to be repelled from the weld.
4. cause abrasive particles to cling to bearing or faying surfaces and increase wear.

Removal of a field (figure 31) may be accomplished in several ways. This random orientation of the magnetic domains can be achieved most effectively by heating the material above its curie temperature. The curie temperature for a low carbon steel is 770°C or 1390°F. When steel is heated above its curie temperature, it will become austenitic and loses its magnetic properties. When it is cooled back down, it will go through a reverse transformation and will contain no residual magnetic field. The material should also be placed with it long axis in an east-west orientation to avoid any influence of the Earth's magnetic field. It is often inconvenient to heat a material above it curie temperature to demagnetize it, so another method that returns the material to a nearly unmagnetized state is commonly used. Subjecting the component to a reversing and decreasing magnetic field will return the dipoles to a nearly random orientation throughout the material. This can be accomplished by pulling a component out and away from a coil with AC passing through it. The same can also be accomplished using an electromagnetic yoke with AC selected. Also, many stationary magnetic particle inspection units come with a demagnetization feature that slowly reduces the AC in a coil in which the component is placed.

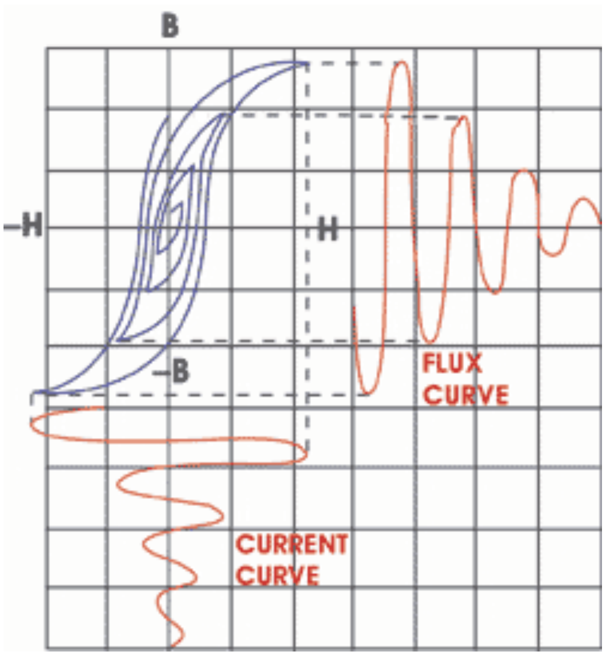


Figure 31: Removal of a magnetic field

3. מכשור:

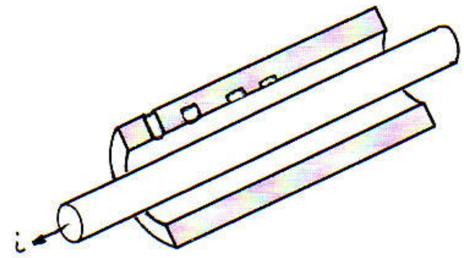
- מכשיר Magnoflux testing המספק זרם ישר עד 2000A.

4. מהלך הניסוי

- לקביעת רגישות השיטה נשתמש בשני דגמים בהם סדרת קדחים בעומקים שונים ונקבע מהו לגילוי קיום שדה מגנטי וזיהוי כיוונו נשתמש בשעון מגנטי ובצלוחית עם מים, עליה נפזר אבקת ברזל.
- לגילוי פגמים נשתמש באבקת ברזל יבשה, לא פלורוסנטית, צבועה באדום או אפור.
- הקדח העמוק ביותר שגורם לריכוז אבקה מעליו.

4.1. <u>מיגנוט מעגלי ישיר</u>

בדוק דגם בצורת צינור שבצידו הפנימי קדחים בעומקים שונים.
השחל את הדגם על מוט שישמש מוליך פנימי. קבע את המוט בין שני נושאי הדגם. באמצעות מפוח אוויר פזר אבקת ברזל על השטח החיצוני והעבר זרם על פי טבלה 1. פזר את האבקה על ידי מפוח אוויר וצפה היכן נשארה. באילו קדחים ניתן להבחין על פי האבקה שנותרה?



בדוק דגם בצורת צינור שבצידו הפנימי סדקים בכיוונים שונים. באיזה מהסדקים ניתן להבחין בשיטה זו?
בדוק דגם מרותך בצורת צינור .האם זיהית פגמי ריתוך בשיטה זו?

4.2. <u>מגנוט אורכי בסליל</u>

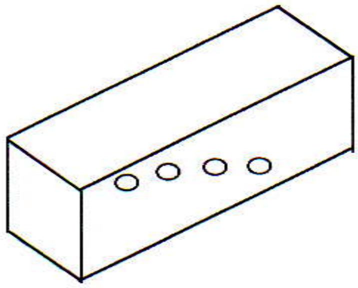
הרכב בין נושאי הדגם סליל. בדוק חלקים סדוקים שתקבל מהמדריך (גל ארכובה, מוט). שים לב לכיוון הסדקים שיתגלו.

4.3. <u>מיגנוט מעגלי בין עוקצים</u>

פזר אבקת ברזל על דגם שטוח בו יש חשד לסדקים. הצמד את עוקצי ספק המתח (prods) והעבר זרם. פזר את האבקה באמצעות המפוח וקבע היכן נשארה.

4.4. <u>מיגנוט אורכי באמצעות אלקטרומגנט</u>

- השתמש באלקטרומגנט פרסה לזיהוי קדחים בדגם כיול בצורת תיבה המכילה סדרת קדחים.
- הצמד את קטבי המגנט משני צידי התיבה. פזר אבקת ברזל, הפעל את האלקטרומגנט וקבע היכן מתרכזת האבקה.



- בדוק האם פלב"ם אוסטניטי הוא פרומגנטי לאחר ריתוך?
- בדוק האם פלב"ם אוסטניטי הוא פרומגנטי לאחר משיכה עמוקה?

5. הנחיות לדו"ח מסכם:

1. תאר את הניסויים שבצעת.
2. סכם איזה סוגי פגמים ניתן לזהות בכל שיטה.
3. מהם היתרונות והמגבלות של שיטת החלקיקים המגנטיים.

6. ביבליוגרפיה:

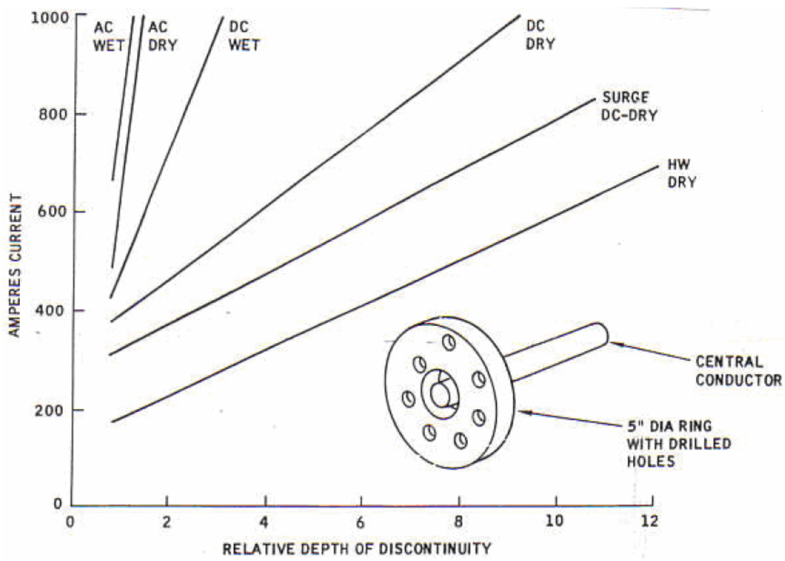
1. http://www.ndt-ed.org/EducationResources/CommunityCollege/communitycollege.htm
2. קובץ ניסיונות מעבדות שנה ג', הנדסת חומרים, 2007-2008, עמ' 214-226
2. "Handbook of nondestructive evaluation", Charles J. Hellier, 2001 (TA 417.2.H45),
3. "Introduction to the non-destructive testing of welded joints", R. Halmshaw, 1996 (TA 492.W4H3555).
4. "Non destructive evaluation: a tool in design, manufacturing, and service", Don E.Bray, 1997 (TA 417.2.B63).
5. "Metals Handbook", 10^{th} ed., ASM , Vol.17 , Non Destructive Evaluation and Quality Control, 1990 (TA 459 A5).

** נלקח מקובץ ניסיונות מעבדות שנה ג', הנדסת חומרים, 2007-2008.

5. נספחים**

5.1. דרישות הזרם

עוצמת הזרם הנדרשת למיגנוט חלקים תלויה בפרמביליות של המתכת, עובי החלק וצורתו וסוג הפגמים שמנסים לזהות (בשיטת החלקיקים המגנטיים ניתן לזהות מפגמים גדולים כמו קדחים מתחת לשטח ועד אינקלוזיות מיקרוסקופיות בפלדה. ציור 1 משווה את הזרם שנדרש לזהות את הקדחים בחלק המשורטט בציור על ידי חלקיקים שפוזרו בקוטר החיצוני. זרם חילופין יעיל לזיהוי פגמים קרובים לשטח והציור מראה שזרם ישר יעיל יותר לזיהוי פגמים עמוקים.



איור 9: הזרם הדרוש לזיהוי קדחים מתחת לפני השטח בשיטות שונות

במיגנוט מעגלי דרוש כ-800-1000A לכל אינץ' קוטר כשמשתמשים בזרם ישר חצי גל (hwde) וב-500-600A עם זרם חילופין.

טבלה 1 מפרטת יותר ערכים מומלצים לקטרים שונים. חומרים וצורות שונות עשויים לדרוש זרמים אחרים. כשיש חלק עם קוטר משתנה ממליצים להשתמש בזרם המתאים לאזור בעל הקוטר הקטן ולבדוק את אותו אזור, אחר כך מגדילים את הזרם כך שיתאים לאזור יותר רחב וכך הלאה. בפעולה בסדר הפוך אפשר לגרום למיגנוט יתר של האזור הצר כך שכשנגיע לבדוק אותו, המיגנוט השאריתי בו יהיה גדול מהמגנוט שנפעיל לבדיקה.

מומלץ להשתמש בדגם כיול שמכיל פגמים במימדים שונים כדי לוודא שהזרם שמשתמשים בו מספיק לזיהוי פגמים בגודל הנדרש.

טבלה 3: זרמים מומלצים למיגנוט מעגלי ישיר או באמצעות מוליך מרכזי

MAXIMUM OUTSIDE DIAMETER IN INCHES*	MAGNETIZING CURRENT (APPROX) IN AMPERES
1/2	500
3/4	750
1	1000
1-1/2	1500
2	2000
2-1/2	2500
3	3000
3-1/2	3500
4	4000

עוצמת השדה במגנוט אורכי באמצעות סליל תלוייה במכפלה של הזרם I במספר הכריכות של הסליל N. למגנוט אורכי דרוש גם שאורך החלק הנבדק L יהיה גדול לפחות כפליים מקוטרו D.

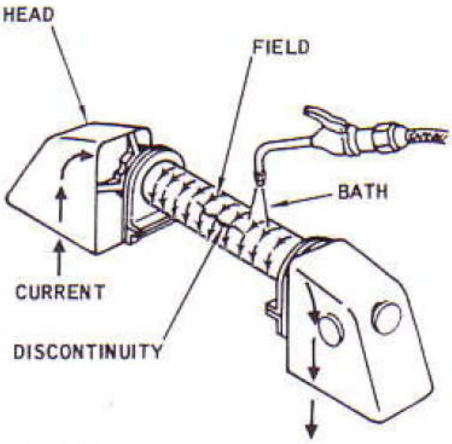
אז הזרם ניתן בביטוי: $I[A]=\dfrac{45000}{\frac{L}{D}}\dfrac{1}{N}$

משוואה זו מתאימה לחלקים העומדים בתנאים הבאים: $2<L/D<15$, $L<18''$, שטח חתך קטן מעשירית שטח המפתח של הסליל והחלק צריך להיות ממוקם ליד קיר פנימי של הסליל ולא במרכזו, כשצירי האורך של החלק והסליל מקבילים.

כשמשתמשים בעוקצים בוחרים את הזרם כך שיהיה הגדול ביותר שלא תהיה הצטברות לא סבירה של אבקה ליד העוקצים.

סיכום והמלצות לבדיקה של חלקים אחדים מתוארות בנספח.

דפי תהליך לבדיקת חלקיקים מגנטיים של חלקים אחדים:

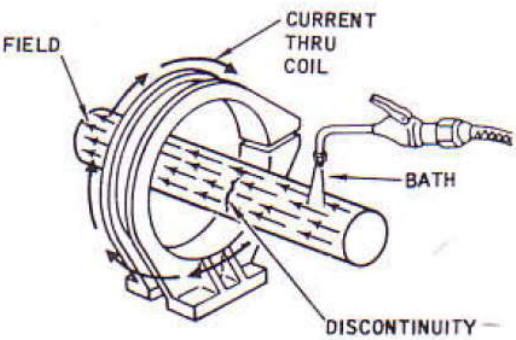


HEAD SHOT

CIRCULAR MAGNETIZATION LOCATES DISCONTINUITIES OCCURRING 45°-90°, TO THE DIRECTION OF THE FIELD.

INSPECT FOR PARTICLE INDICATIONS SHOWING LONGITUDINAL DISCONTINUITIES - MARK DISCONTINUITIES.

SOLID CYLINDRICAL ARTICLES		
EXAMPLE	APPROXIMATE CURRENT	
	HEAD SHOT AMPERES	COIL SHOT AMPERES
1.0" DIA. ROD	500-1000	300-700
3.0" DIA. ROD	1500-3000	1000-MAX.
1.5" DIA. BOLT	200-500	100-300
CONTROL YOUR AMPERAGE ACCORDING TO APPLICABLE SPECIFICATIONS.		



COIL SHOT

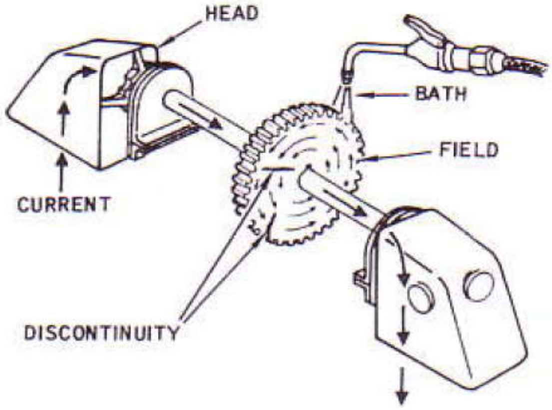
LONGITUDINAL MAGNETIZATION LOCATES TRANSVERSE DISCONTINUITIES.

INSPECT FOR PARTICLE INDICATIONS SHOWING TRANSVERSE DISCONTINUITIES.

NOTE

EFFECTIVE LENGTH MAGNETIZED BY COIL SHOT IS A FEW INCHES EITHER SIDE OF COIL. MAXIMUM LENGTH OF ARTICLE COVERED BY ONE SHOT IS 18 INCHES. ON LONG ARTICLES, USE REPEATED SHOTS AND BATHS DOWN THE LENGTH OF ARTICLE. PUT SMALL ARTICLES CLOSE TO COIL BODY.

Figure 5-1. Magnetization of Solid Cylindrical Specimen

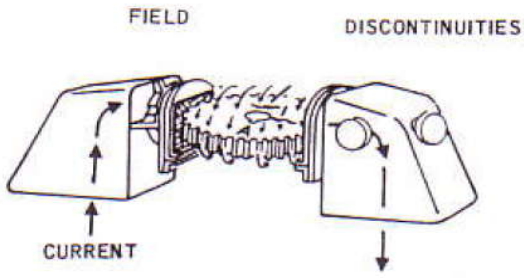


SHOT NO. 1 — HEAD SHOT (WITH CENTRAL CONDUCTOR)

CENTRAL CONDUCTOR IS USED FOR CIRCULAR MAGNETIZATION TO LOCATE DISCONTINUITIES ACROSS GEAR.

INSPECT FOR PARTICLE INDICATIONS SHOWING DISCONTINUITIES - MARK ALL INDICATIONS.

LARGE DIAMETER DISCS, GEARS, ETC.		
EXAMPLE	APPROXIMATE CURRENT	
	SHOT NO. 1 AMPERES	SHOT NOS. 2 & 3 AMPERES
MEDIUM DIA. GEARS—4" D. 8" D.	2000-MAX.	1500-MAX.
REDUCTION GEAR—15" D.	2000-MAX. (NOTE "A")	1000-MAX.
CAM RING & GEAR	2000-MAX. (SEE NOTE)	1000-2500
CONTROL YOUR AMPERAGE BY APPLICABLE SPECIFICATIONS.		

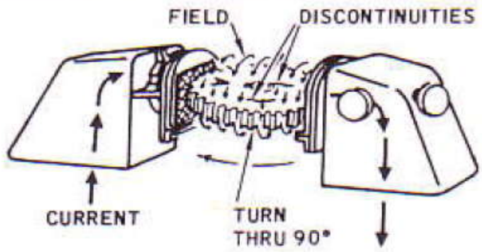


SHOT NO. 2 — FIRST HEAD SHOT ACROSS GEAR

CURRENT PASSING ACROSS DIAMETER THROUGH GEAR LOCATES DISCONTINUITIES EXTENDING AROUND THE GEAR.

USE COPPER-BRAID, NEOPRENE-BACKED CONTACTS ON HEADS TO AVOID BURNING GEAR TEETH AT CONTACT POINTS.

INSPECT FOR PARTICLE INDICATIONS SHOWING DISCONTINUITIES - MARK ALL DISCONTINUITIES.



SHOT NO. 3 — SECOND HEAD SHOT ACROSS GEAR

TURN THE GEAR 90° AND SHOOT AGAIN ACROSS DIAMETER.

INSPECT FOR PARTICLE INDICATIONS SHOWING DISCONTINUITIES - MARK ALL DISCONTINUITIES.

TURNING THE GEAR 90° AND SHOOTING ACROSS IT TWICE WILL REVEAL ALL DISCONTINUITIES EXTENDING AROUND GEAR.

NOTE: LARGE DIAMETER RINGS WITH LARGE CENTER HOLE. REST ON CONDUCTOR, INSPECT ONLY NEAR CONDUCTOR. REPEAT AROUND CIRCUMFERENCE.

Figure 5-3. Magnetization of Large Diameter Discs, Gears, etc.

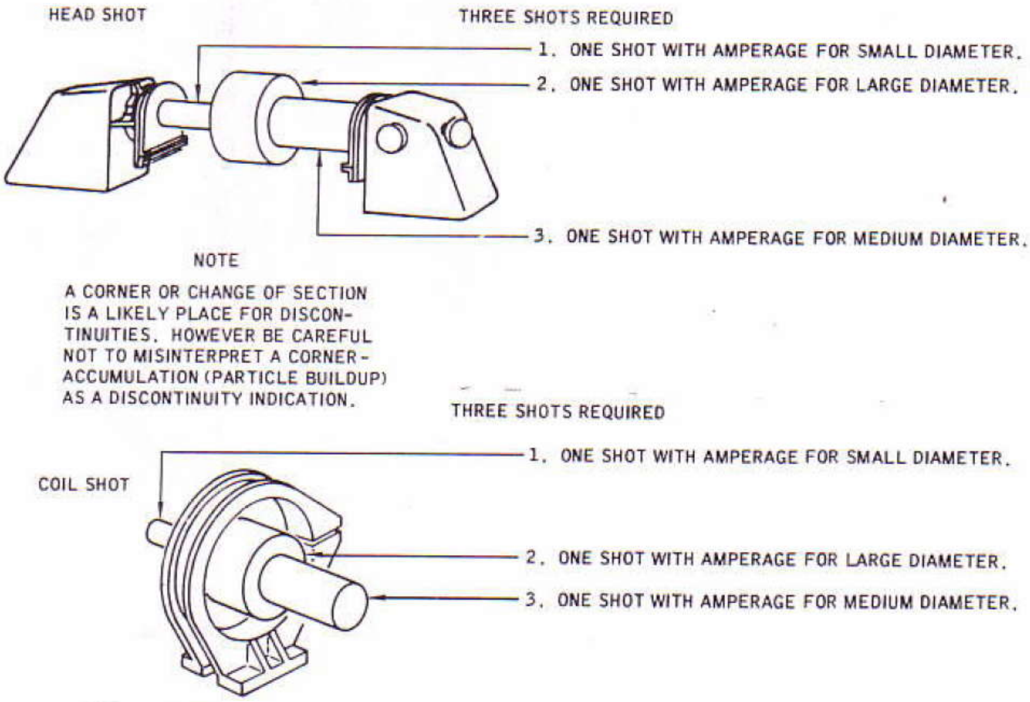


Figure 5-2. Magnetization of Cylindrical Specimen w-Var: Diameter

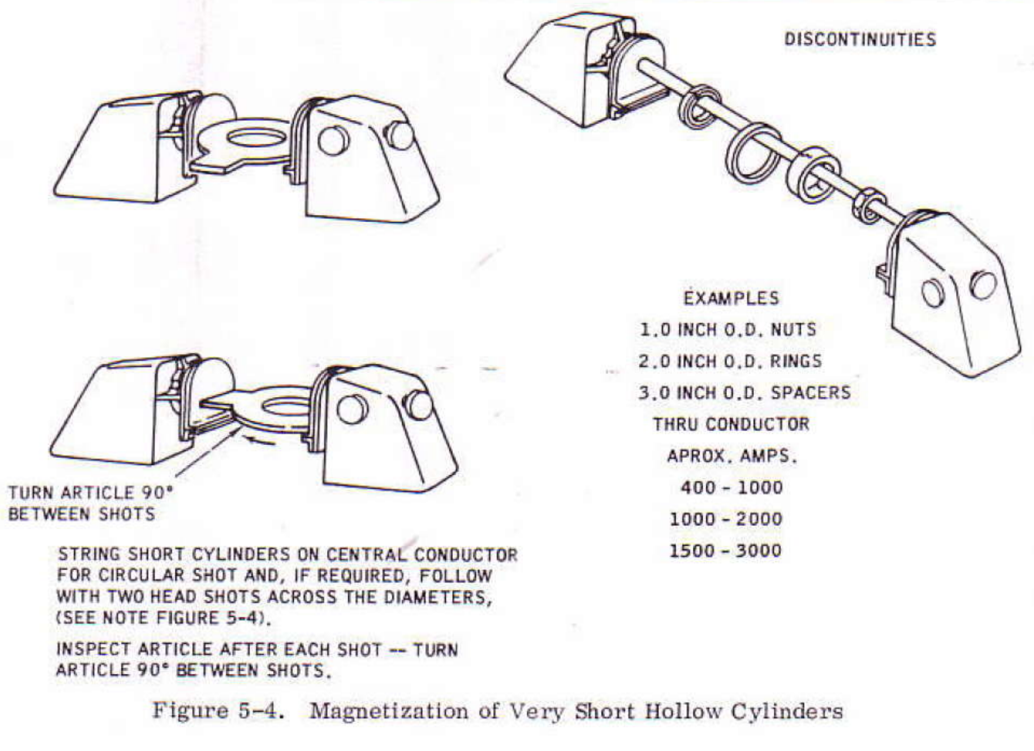


Figure 5-4. Magnetization of Very Short Hollow Cylinders