PDHonline Course M468 (6 PDH)

Common Nondestructive Testing_NDT - Part 1

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Introduction:

Nondestructive examination (NDE) methods of inspection make it possible to verify compliance to the standards by examining the surface and subsurface of welding and engineered materials for construction purposes. **Six** basic inspection methods are commonly used: **Visual, Liquid Penetrant, Magnetic Particle,** (described in Part 1**), Ultrasonic, Eddy Current and Radiographic,** (described in Part 2**)**.

1. Visual Inspection (VT):

Visual inspection is often the most cost-effective method, but it must take place prior to, during and after welding. Many standards require its use before other methods, because there is no point in submitting an obviously bad weld to sophisticated inspection techniques. The **ANSI/AWS D1.1, Structural Welding Code-Steel**, states, "Welds subject to nondestructive examination shall have been found acceptable by visual inspection". Visual inspection requires little equipment. Aside from good eye sight and sufficient light, all it takes is a pocket rule, a weld size gauge, a magnifying glass, and possibly a straight edge and square for checking straightness, alignment and perpendicularity.

> "Visual inspection is the best buy in NDE, but it must take place prior to, during and after welding."

Before the first welding arc is struck, materials should be examined to see if they meet specifications for quality, type, size, cleanliness and freedom from defects. Grease, paint, oil, oxide film or heavy scale should be removed. The pieces to be joined should be checked for flatness, straightness and dimensional accuracy. Likewise, alignment, fit-up and joint preparation should be examined. Finally, process and procedure variables should be verified, including electrode size and type, equipment settings and provisions for preheat or postheat. All of these precautions apply regardless of the inspection method being used.

During fabrication, visual examination of a weld bead and the end crater may reveal problems such as cracks, inadequate penetration, and gas or slag inclusions. Among the weld detects that can be recognized visually are cracking, surface slag in inclusions, surface porosity and undercut. On simple welds, inspecting at the beginning of each operation and periodically as work progresses may be adequate.

Where more than one layer of filler metal is being deposited, however, it may be desirable to inspect each layer before depositing the next. The root pass of a multipass weld is the most critical to weld soundness. It is especially susceptible to cracking, and because it solidifies quickly, it may trap gas and slag. On subsequent passes, conditions caused by the shape of the weld bead or changes in the joint configuration can cause further cracking, as well as undercut and slag trapping. Repair costs can be minimized if visual inspection detects these flaws before welding progresses. VT can only locate defects in the weld surface.

Visual inspection at an early stage of production can also prevent underwelding and overwelding. Welds that are smaller than called for in the specifications cannot be tolerated. Beads that are too large increase costs unnecessarily and can cause distortion through added shrinkage stress.

After welding, visual inspection can detect a variety of surface flaws, including cracks, porosity and unfilled craters, regardless of subsequent inspection procedures. Dimensional variances, warpage and appearance flaws, as well as weld size characteristics, can be evaluated.

Before checking for surface flaws, welds must be cleaned of slag. Shot-blasting should not be done before examination, because the peening action may seal fine cracks and make them invisible. The **AWS D1.1** *Structural Welding Code*, for example, does not allow peening "on the root or surface layer of the weld or the base metal at the edges of the weld."

2. Liquid Penetrant Inspection (PT):

Liquid penetrant inspection (PT, LPT or LPI) is a method that is used to reveal surface breaking flaws by bleed out of a colored or fluorescent dye from the flaw. 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". After removal and careful cleaning, the surface is then coated with a fine suspension of chalk in alcohol, so that a white surface layer is formed once the alcohol had evaporated.

The whitewash provides a contrasting background, and draws the oil back out of the surface flaws allowing them to be interpreted and evaluated. Penetrant Inspection method is related to fluids, pressure, visibility, entrapment, surface tension, and viscosity that are constants, and so relevant today, as they were during the early development of this valuable inspection process.

A very early surface inspection technique involved the rubbing of carbon black on glazed pottery, whereby the carbon black would settle in surface cracks rendering them visible. Later, it became the practice in railway workshops to examine iron and steel components by the "**oil and whiting**" method. In this method, heavy oil commonly available in railway workshops was diluted with kerosene in large tanks so that locomotive parts, such as wheels could be submerged.

Liquid penetrant testing became in use from approximately 1940, when the magnetic particle method was introduced and found to be more sensitive for ferromagnetic iron and steels. The surface under examination was coated with a lacquer, and after drying, the sample was caused to vibrate by the tap of a hammer. The vibration causes the brittle lacquer layer to crack generally around surface defects. The brittle lacquer has been used primarily to show the distribution of stresses in a part and not for finding defects.

In 1942, Magnaflux introduced the Zyglo system of penetrant testing (PT) inspection where fluorescent dyes were added to the liquid penetrant. These dyes would then fluoresce when exposed to ultraviolet light (sometimes referred to as "black light") rendering indications from cracks and other surface flaws more readily visible to inspectors.

Many of these early developments were carried out by Magnaflux in Chicago, IL, USA in association with Switzer Bros., Cleveland, OH, USA. More effective penetrating oils containing highly visible (usually red) dyes were developed by Magnaflux to enhance flaw detection capability. This method, known as the visible or color contrast dye penetrant method, is still used quite extensively today.

1. Detectability of Flaws:

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. When a visible dye penetrant inspection is performed, the penetrant materials are formulated using a bright red dye, providing a high level of contrast between the white developers.

In other words, the developer serves as a high contrast background, as well as a blotter to pull the trapped penetrant from the flaw. When a fluorescent penetrant inspection is performed, the penetrant materials are formulated to glow brightly and to give off light at a wavelength that the eye is most sensitive to under dim lighting conditions.

2. Steps of a Liquid Penetrant Inspection:

- **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.

- **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.

- **Penetrant Dwell**: The penetrant is left on the surface for a sufficient time to allow as much penetrant as possible to seep into a defect. Penetrant dwell time is the total time that the penetrant is in contact with the surface part. Dwell times are recommended by the penetrant producers or required by a defined specification. Minimum dwell times range from five to 60 minutes. The ideal dwell time is often determined by experimentation and may be very specific to a particular application.

- **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. 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.

- **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. Developers come in a variety of forms that may be applied by dusting (dry powdered), dipping, or spraying (wet developers).

- **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.

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

- **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.

3. 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.

LPI offers flexibility in performing inspections because it can be applied in a large variety of applications ranging from automotive spark plugs to critical aircraft components. Penetrant materials can be applied with a spray can or a cotton swab to inspect for flaws known to occur in a specific area or it can be applied by dipping or spraying to quickly inspect large areas.

In the image above, visible dye penetrant is being locally applied to a highly loaded connecting point to check for fatigue cracking. Liquid penetrant inspection can only be used to inspect for flaws that break the surface of the sample. As mentioned above, one of the major limitations of a penetrant inspection is that flaws must be open to the surface. 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.

4. Advantages and Disadvantages of Penetrant Testing:

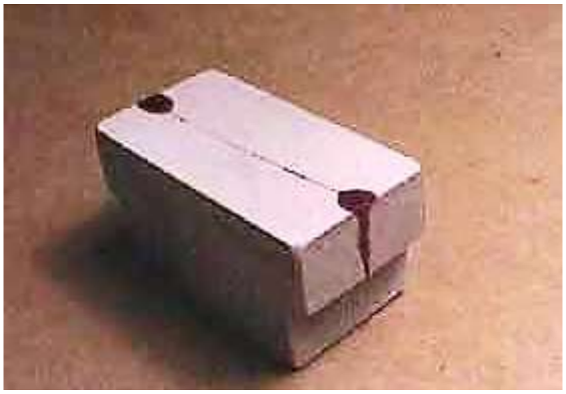
a. Advantages:

- 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.

b. Disadvantages:

- Only surface breaking defects can be detected.
- Only materials with a relatively nonporous surface can be inspected.
- Pre-cleaning 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.

5. Penetrant Testing Conditions:



The penetrant materials used today are much more sophisticated than the kerosene and whiting first used by railroad inspectors near the turn of the 20th century. Today's penetrants are carefully formulated to produce the level of sensitivity desired by the inspector. 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 fluid so it can be drawn back to the surface of the part through the drying and developing steps;

- Remain in the defect but remove easily from the surface of the part;
- Be highly visible or fluoresce brightly to produce easy to see indications;
- Not be harmful to the material being tested or the inspector.

All penetrant materials do not perform the same and are not designed to perform the same. Penetrant manufactures have developed different formulations to address a variety of inspection applications. Some applications call for the detection of the smallest defects possible and have smooth surfaces where the penetrant is easy to remove. In other applications, the rejectable defect size may be larger and a penetrant formulated to find larger flaws can be used.

The penetrants that are used to detect the smallest defect will also produce the largest amount of irrelevant indications. Penetrant materials are classified in the various industry and government specifications by their physical characteristics and their performance. Aerospace Material Specification (AMS) 2644, Inspection Material, is now the primary specification used in the USA to control materials.

Historically, Military Standard 25135, Inspection Materials, Penetrants, has been the primary document for specifying penetrants but this document is slowly being phased out and replaced by AMS 2644. Other specifications such as ASTM 1417, Standard Practice for Liquid Penetrant Examinations, may also contain information on the classification of penetrant materials but they are generally referred back to MIL-I-25135 or AMS 2644. Penetrant materials come in two basic types. These types are listed below:

- **Type 1** - Fluorescent Penetrants;
- **Type 2** - Visible Penetrants.

Fluorescent penetrants 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 classified by the method used to remove the excess penetrant. The common four methods are listed below:

- **Method A** - Water Washable;
- **Method B** - Post-Emulsifiable, Lipophilic;
- **Method C** - Solvent Removable;
- **Method D** - Post-Emulsifiable, Hydrophilic.

a. Method A: Consists of **water washable penetrants** can be removed from the part by rinsing with water alone and is the most economical. These penetrants contain an emulsifying agent (detergent) that makes it possible to wash the penetrant from the surface with water alone. Water washable penetrants are sometimes referred to as **self-emulsifying** systems.

b. Method B: Consists of **post-emulsifiable penetrants** that come in two varieties, **lipophilic and hydrophilic**. In post-emulsifiers, lipophilic systems, the penetrant is oil soluble and interacts with the **oil-based** emulsifier to make removal possible.

c. Method C: Consists of a **solvent removable**, which is used primarily for inspecting small localized areas. This method requires hand wiping the surface with a cloth moistened with the solvent remover, however, it is too labor intensive for most production situations.

d. Method D: Consists of **post-emulsifiable-hydrophilic penetrants** that use an emulsifier, which is a **water soluble** detergent that 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.

Obs.: Penetrants are then classified based on the strength or detectability of the indication that is produced for a number of very small and tight fatigue cracks. The five sensitivity levels are shown below:

- Level ½ - Ultra Low Sensitivity;
- Level 1 - Low Sensitivity;
- Level 2 - Medium Sensitivity;
- Level 3 - High Sensitivity;
- Level 4 - Ultra-High Sensitivity.

The major US government and industry specifications currently rely on the US Air Force Materials Laboratory at Wright-Patterson Air Force Base to classify penetrants into one of the five sensitivity levels. This procedure uses titanium and Inconel specimens with small surface cracks produced in low cycle fatigue bending to classify penetrant systems. The brightness of the indication produced is measured using a photometer. The sensitivity levels and the test procedure used can be found in Military Specification MIL-I-25135 and Aerospace Material Specification 2644,

6. Penetrant Inspection Materials:

An interesting note about the sensitivity levels is that only four levels were originally planned. However, when some penetrants were judged to have sensitivities significantly less than most others in the level 1 category, the ½ level was created. An excellent historical summary of the development of test specimens for evaluating the performance of penetrant materials can be found in the following reference.

a. Liquid Penetrant: The industry and military specifications that control materials and their use, all stipulate certain physical properties of the penetrant materials that must be met. Some of these requirements address the safe use of the materials, such as toxicity, low flash point, and corrosiveness, and other requirements address storage and contamination issues.

Other properties that are thought to be primarily responsible for the performance or sensitivity of the penetrants. The properties of penetrant materials that are controlled by AMS 2644 and MIL-I-25135E include flash point, surface wetting capability, viscosity, color, brightness, ultraviolet stability, thermal stability, water tolerance, and removability.

b. Emulsifiers: When removal of the penetrant from a defect due to over-washing of the part is a concern, a post-emulsifiable penetrant system can be used. Post-emulsifiable penetrants require a separate emulsifier to break the penetrant down and make it water-washable. Most penetrant inspection specifications classify penetrant systems into four methods, as described above, of excess penetrant removal.

The **Method C** relies on a solvent cleaner to remove the penetrant from the part being inspected. The **Method A** has emulsifiers built into the penetrant that makes it possible to remove the excess penetrant with a simple water wash. **Methods B and D** require an additional processing step where a separate emulsification agent is applied to make the excess penetrant more removable with water wash. **Lipophilic** emulsification systems are **oil-based** materials that are supplied in ready-to-use form. **Hydrophilic** systems are **water-based** and supplied as a concentrate that must be diluted with water prior to use.

The **lipophilic emulsifiers (Method B)** were introduced in the late 1950's and work with both a chemical and mechanical action. After the emulsifier has coated the surface of the object, mechanical action starts to remove some of the excess penetrant as the mixture drains from the part. During the emulsification time, the emulsifier diffuses into the remaining penetrant and the resulting mixture is easily removed with a water spray.

The **hydrophilic emulsifiers (Method D)** also remove the excess penetrant with mechanical and chemical action but the action is different because no diffusion takes place. Hydrophilic emulsifiers are basically detergents that contain solvents and surfactants. The hydrophilic emulsifier breaks up the penetrant into small quantities and prevents these pieces from recombining or reattaching to the surface of the part. The mechanical action of the rinse water removes the displaced penetrant from the part and causes fresh remover to contact and lift newly exposed penetrant from the surface.

The hydrophilic post-emulsifiable method **(Method D)** was introduced in the mid 1970's. Since it is more sensitive than the lipophilic post emulsifiable method it has made the later method virtually obsolete. The major advantage of hydrophilic emulsifiers is that they are **less sensitive to variation** in the contact and removal time.

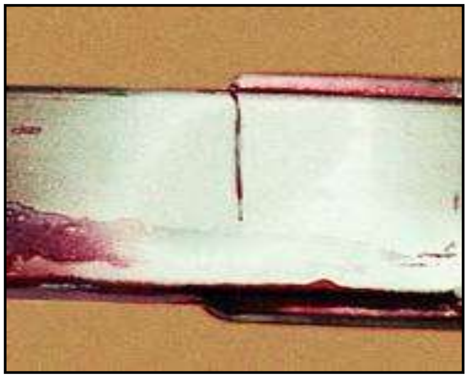
While emulsification time should be controlled as closely as possible, a variation of one minute or more in the contact time will have little effect on flaw detectability when a hydrophilic emulsifier is used. However, a variation of as little as 15 to 30 seconds can have a significant effect when a lipophilic system is used.

7. Surface Wetting Capability:

As previously mentioned, one of the important characteristics of a liquid penetrant material is its ability to freely wet the surface of the object being inspected. At the liquid-solid surface interface, if the molecules of the liquid have a stronger attraction to the molecules of the solid surface than to each other (the adhesive forces are stronger than the cohesive forces), wetting of the surface occurs. Alternately, if the liquid molecules are more strongly attracted to each other than the molecules of the solid surface (the cohesive forces are stronger than the adhesive forces), the liquid beads-up and does not wet the surface of the part.

One way to quantify a liquid's surface wetting characteristics is to measure the contact angle of a drop of liquid placed on the surface of an object. The contact angle is the angle formed by the solid/liquid interface and the liquid/vapor interface measured from the side of the liquid. (See figure below.) Liquids wet surfaces when the contact angle is less than 90 degrees. For a penetrant material to be effective, the contact angle should be as small as possible. In fact, the contact angle for most liquid penetrants is very close to zero degrees.

Wetting ability of a liquid is a function of the surface energies of the solid-gas interface, the liquid-gas interface, and the solid-liquid interface. The surface energy across an interface or the surface tension at the interface is a measure of the energy required to form a unit area of new surface at the interface. The intermolecular bonds or cohesive forces between the molecules of a liquid cause surface tension.



When the liquid encounters another substance, there is usually an attraction between the two materials. The adhesive forces between the liquid and the second substance will compete against the cohesive forces of the liquid. Liquids with weak cohesive bonds and a strong attraction to another material (or the desire to create adhesive bonds) will tend to spread over the material. Liquids with strong cohesive bonds and weaker adhesive forces will tend to bead-up or form a droplet when in contact with another material.

In liquid penetrant testing, there are usually three surface interfaces involved, the solid-gas interface, the liquid-gas interface, and the solid-liquid interface. For a liquid to spread over the surface of a part, two conditions must be met. First, the surface energy of the solid-gas interface must be greater than the combined surface energies of the liquid-gas and the solid-liquid interfaces. Second, the surface energy of the solid-gas interface must exceed the surface energy of the solid-liquid interface.

A penetrant's wetting characteristics are also largely responsible for its ability to fill a void. Penetrant materials are often pulled into surface breaking defects by capillary action. The capillary force driving the penetrant into the crack is a function of the surface tension of the liquid-gas interface, the contact angle, and the size of the defect opening.

8. Color and Fluorescent Brightness:

a. Penetrant Color and Fluorescence: The color of the penetrant material is of obvious importance in a visible dye penetrant inspection, as the dye must provide good contrast against the developer or part being inspected. Remember from the earlier discussion of contrast sensitivity that generally the higher the contrast, the easier objects are to see. The dye used in visible dye penetrant is usually vibrant red but other colors can be purchased for special applications.

When fluorescent materials are involved, the effect of color and fluorescence is not so straightforward. LPI materials fluoresce because they contain one or more dyes that absorb electromagnetic radiation over a particular wavelength and the absorption of photons leads to changes in the electronic configuration of the molecules. Since the molecules are not stable at this higher energy state, they almost immediately re-emit the energy. There is some energy loss in the process and this causes photons to be re-emitted at a slightly longer wavelength that is in the visible range.

The radiation absorption and emission could take place a number of times until the desired color and brightness are achieved. Two different fluorescent colors can be mixed to interact by a mechanism called cascading. The emission of visible light by this process involves one dye absorbing ultraviolet radiation to emit a band of radiation that makes a second dye glow. Human eyes are the most commonly used sensing devices, most penetrants are designed to fluoresce as close as possible to the eyes' peak response.

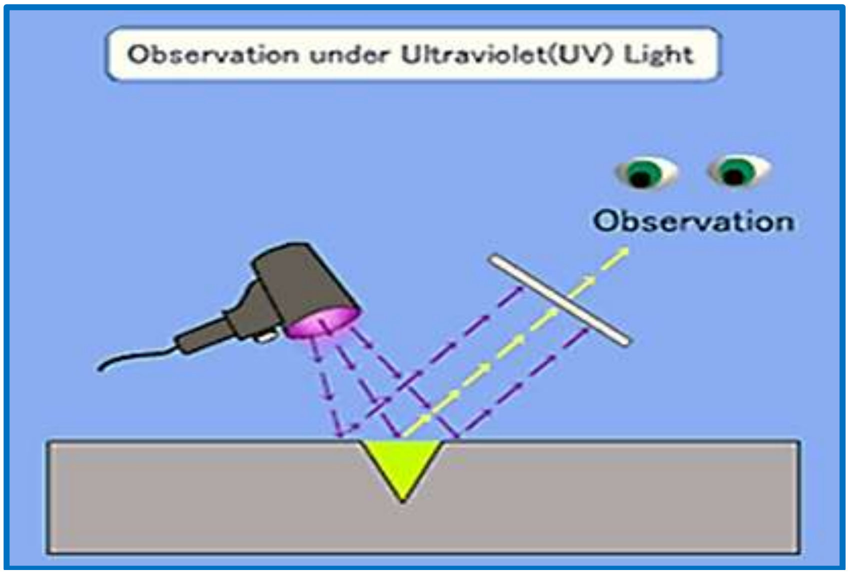
b. Penetrant Brightness: Fluorescent brightness was erroneously once thought to be the controlling factor with respect to **flaw detection** sensitivity. Measurements have been made to evaluate the intrinsic brightness of virtually all commercially available penetrants and they all have about the same brightness. Intrinsic brightness values are determined for thick liquid films but the dimensional threshold of fluorescence is a more important property. The measurement of fluorescent brightness is detailed in ASTM E-1135, "Standard Test Method for Comparing the Brightness of Fluorescent Penetrants."

9. Ultraviolet and Thermal Stability:

Exposure to intense ultraviolet light and elevated temperatures can have a negative effect on fluorescent penetrant indications. Fluorescent materials can lose their brightness after a period of exposure to high intensity UV light. One study measured the intensity of fluorescent penetrant indications on a sample that was subjected to multiple UV exposure cycles.

Each cycle consisted of 15 minutes of 800 microwatt/cm² UV light and 2.5 minutes of 1500 microwatt/cm² UV light. Two penetrants were tested; water washable, level 3 and a post emulsifiable, level 4. The results from the study showed that the indications from both penetrants faded with increased UV exposure. After eight exposure cycles, the brightness of the indications were less than one half their original values. At an elevated temperature, penetrants experienced heat degradation or "heat fade". Test conditions were:

1. Evaporates the more volatile constituents, which increases viscosity and affects rate of penetration;
2. Alters wash characteristics;
3."Boils off" chemicals that prevent separation and gelling of water soluble penetrants;
4. Kills the fluorescence of tracer dyes.



a. Loss of Energy: The loss of energy can involve a "radioactive" process, such as fluorescence or "non-radioactive processes". A fourth degradation mechanism involves the molecules of the penetrant materials. The phenomenon of fluorescence involves electrons that are delocalized in a molecule. These electrons are not specifically associated with a given bond between two atoms. When a molecule takes up sufficient energy for the excitation source, the delocalized bonding electrons rise to a higher electronic state. After excitation, the electrons will normally lose energy and return to the lowest energy state.

Non-radioactive processes include relaxation by molecular collisions, thermal relaxation, and chemical reaction. Heat causes the number of molecular collisions to increase, which results in more collision relaxation and less fluorescence. This explanation is only valid when the part and the penetrant are at an elevated temperature. When the materials cool, the fluorescence will return. However, while exposed to elevated temperatures, penetrant solutions dry faster.

As the molecules become more closely packed in the dehydrated solution, collision relaxation increases and fluorescence decreases. This effect has been called "concentration quenching" and experimental data shows that as the dye concentration is increased, fluorescent brightness initially increases but reaches a peak and then begins to decrease. Airflow over the surface on the part will also speed evaporation of the liquid carrier, so it should be kept to a minimum to prevent a loss of brightness.

Generally, thermal damage occurs when fluorescent penetrant materials are heated above 71^{o}C (160^{o}F). It should be noted that the sensitivity of an FPI inspection can be improved if a part is heated prior to applying the penetrant material, but the temperature should be kept below 71^{o}C (160^{o}F). Some high temperature penetrants in use today are formulated with dyes with high melting points, greatly reducing heat related problems. Penetrants also have high boiling points and the heat related problems are greatly reduced.

However, a loss of brightness can still take place when the penetrant is exposed to elevated temperatures over an extended period of time. When one heat resistant formulation was tested, a 20 % reduction was measured after the material was subjected to 163^{o}C (325^{o}F) for 273 hours. The various types of fluorescent dyes commonly employed in today's penetrant materials begin decomposition at 71^{o}C (160^{o}F). When the temperature approaches 94^{o}C (200^{o}F), there is almost total attenuation of fluorescent brightness of the composition and sublimation of the fluorescent dyestuffs.

b. Removability: Removing the penetrant from the surface of the sample, without removing it from the flaw, is one of the most critical operations of the penetrant inspection process. The penetrant must be removed from the sample surface as completely as possible to limit background fluorescence. In order for this to happen, the adhesive forces of the penetrant must be weak enough that they can be broken by the removal methods used. Proper formulation of the penetrant materials provides the correct balancing of these forces.

In order for the penetrant to have good surface wetting characteristics, the adhesive forces (forces of attraction between the penetrant and the solid surface being inspected) must be stronger than the cohesive forces (forces holding the liquid together). Another consideration in the formulation of the penetrant liquid is that it should not easily commingle and become diluted by the cleaning solution. Dilution of the penetrant liquid will affect the concentration of the dye and reduce the dimensional threshold of fluorescence.

c. Developers: The role of the developer is to pull the trapped penetrant material out of defects and spread it out on the surface of the part so it can be seen by an inspector. The fine developer particles both reflect and refract the incident ultraviolet light, allowing more of it to interact with the penetrant, causing more efficient fluorescence. The developer also allows more light to be emitted through the same mechanism. This is why indications are brighter than the penetrant itself under UV light. Another function that some developers perform is to create a white background so there is a greater degree of contrast between the indication and the surrounding background.

10. Developer Forms:

The AMS 2644 and Mil-I-25135 classify developers into six standard forms. The developer classifications are based on the method that the developer is applied. The developer can be applied as a dry powder, or dissolved or suspended in a liquid carrier. Each of the developer forms has advantages and disadvantages. These forms are listed below:

Form a - Dry Powder;
Form b - Water Soluble;
Form c - Water Suspendable;
Form d - Nonaqueous Type 1 Fluorescent (Solvent Based);
Form e - Nonaqueous Type 2 Visible Dye (Solvent Based);
Form f - Special Applications.

a. Form a - Dry Powder: Dry powder developer is generally considered to be the least sensitive but it is inexpensive to use and easy to apply. Dry developers are white, fluffy powders that can be applied to a thoroughly dry surface in a number of ways. The developer can be applied by dipping parts in a container of developer, or by using a puffer to dust parts with the developer.

Parts can also be placed in a dust cabinet where the developer is blown around and allowed to settle on the part. Electrostatic **powder spray guns** are also available to apply the developer. The goal is to allow the developer to come in contact with the whole inspection area.

Unless the part is electrostatically charged, the powder will only adhere to areas where trapped penetrant has wet the surface of the part. The penetrant will try to wet the surface of the penetrant particle and fill the voids between the particles, which brings more penetrant to the surface of the part where it can be seen. Since dry powder developers only stick to the area where penetrant is present, the dry developer does not provide a uniform white background as the other forms of developers do.

Having a uniform light background is very important for a visible inspection to be effective and since dry developers do not provide one, they are seldom used for visible inspections. When a dry developer is used, indications tend to stay bright and sharp since the penetrant has a limited amount of room to spread.

b. Form b - Water Soluble: As the name implies, water soluble developers consist of a group of chemicals that are dissolved in water and form a developer layer when the water is evaporated away. The best method for applying water soluble developers is by spraying it on the part. The part can be wet or dry. Dipping, pouring, or brushing the solution on to the surface is sometimes used but these methods are less desirable.

Aqueous developers contain wetting agents that cause the solution to function much like dilute hydrophilic emulsifier and can lead to additional removal of entrapped penetrant. Drying is achieved by placing the wet but well drained part in a recirculating, warm air dryer with the temperature held between 70 and 75°F. If the parts are not dried quickly, the indications will be blurred and indistinct. Properly developed parts will have an even, pale white coating over the entire surface.

c. Form c - Water Suspendable: Water suspendable developers consist of insoluble developer particles suspended in water. Water suspendable developers require frequent stirring or agitation to keep the particles from settling out of suspension. Water suspendable developers are applied to parts in the same manner as water soluble developers. Parts coated with a water suspendable developer must be forced dried just as parts coated with a water soluble developer are forced dried. The surface of a part coated with a water suspendable developer will have a slightly translucent white coating.

d. Form d/e - Nonaqueous: Nonaqueous developers suspend the developer in a volatile solvent and are typically applied with a spray gun. Nonaqueous developers are commonly distributed in aerosol spray cans for portability. The solvent tends to pull penetrant from the indications by solvent action.

Since the solvent is highly volatile, forced drying is not required. A nonaqueous developer should be applied to a thoroughly dried part to form a slightly translucent white coating.

e. Form f - Special Applications: Plastic or lacquer developers are special developers that are primarily used when a permanent record of the inspection is required.

11. Selection of a Penetrant Technique:

The selection of a liquid penetrant system is not a straightforward task. There are a variety of penetrant systems and developer types that are available for use, and one set of penetrant materials will not work for all applications. Many factors must be considered when selecting the penetrant materials for a particular application. These factors include the sensitivity required, materials cost, number of parts, size of area requiring inspection, and portability.

When sensitivity is the primary consideration for choosing a penetrant system, the first decision that must be made is whether to use fluorescent penetrant or visible dye penetrant. Fluorescent penetrants are generally more capable of producing a detectable indication from a small defect.

Also, the human eye is more sensitive to a light indication on a dark background and the eye is naturally drawn to a fluorescent indication. To the left of the contrast ratio of one, the spot is darker than the background (representative of visible dye penetrant testing); and to the right of one, the spot is brighter than the background (representative of fluorescent penetrant inspection).

Each of the three curves right or left of the contrast ratio of one are for different background brightness (in foot-Lamberts), but simply consider the general trend of each group of curves right or left of the contrast ratio of one. The curves show that for indication larger than 0.076 mm (0.003 inch) in diameter, it does not really matter if it is a dark spot on a light background or a light spot on a dark background.

However, when a dark indication on a light background is further reduced in size, it is no longer detectable even though contrast is increased. Furthermore, with a light indication on a dark background, indications down to 0.003 mm (0.0001 inch) were detectable when the contrast between the flaw and the background was high. From this data, it can be seen why a fluorescent penetrant offers an advantage over a visible penetrant for finding very small defects.

Data presented by De Graaf and De Rijk supports this statement. They inspected "identical" fatigue cracked specimens using a red **dye penetrant** and a **fluorescent dye** penetrant. The **fluorescent penetrant** found **60 defects** while the **visible dye** was only able to find **39 of the defects**. Under certain conditions, the visible penetrant may be a better than a simple choice. When fairly large defects are the subject of the inspection, a high sensitivity system may not be warranted and may result in a large number of irrelevant indications.

Visible dye penetrants have also been found to give better results when surface roughness is high or when flaws are located in areas such as weldments. Since visible dye penetrants do not require a darkened area for the use of an ultraviolet light, visible systems are more easy to use in the field. Solvent removable penetrants, when properly applied, can have the highest sensitivity and are very convenient to use. However, they are usually not practical for large area inspection or in high-volume production settings.

Another consideration in the selection of a penetrant system is whether water washable, post-emulsifiable or solvent removable penetrants will be used. **Post-emulsifiable** systems are designed to reduce the possibility of **over-washing**, which is one of the factors known to reduce sensitivity. However, these systems add another step, and thus cost, to the inspection process. Penetrants are evaluated by the US Air Force according to the requirements in MIL-I-25135 and each penetrant system is classified into one of five sensitivity levels.

This procedure uses titanium and Inconel specimens with small surface cracks produced in low cycle fatigue bending to classify penetrant systems. The brightness of the indications produced after processing a set of specimens with a particular penetrant system is measured using a photometer. A procedure for producing and evaluating the penetrant qualification specimens was reported on by Moore and Larson at the 1997 ASNT Fall Conference.

The most commercially penetrant materials are listed in the Qualified Products List of MIL-I-25135 according to their type, method and sensitivity level. Visible dye and dual-purpose penetrants are not classified into sensitivity levels as fluorescent penetrants are. The sensitivity of a visible dye penetrant is regarded as level 1 and largely dependent on obtaining good contrast between the indication and the background.

a. Penetrant Application: The penetrant material can be applied in a number of different ways, including **spraying, brushing, or immersing the parts** in a penetrant bath. The method of penetrant application has little effect on the inspection sensitivity but an electrostatic spraying method is reported to produce slightly better results than other methods.

Once the part is covered in penetrant it must be allowed to dwell so the penetrant has time to enter any defect present. There are basically two dwell mode options, immersion-dwell (keeping the part immersed in the penetrant during the dwell period) and drain-dwell (letting the part drain during the dwell period).

Prior to a study by Sherwin, the immersion-dwell mode was generally considered to be more sensitive but recognized to be less economical because more penetrant was washed away and emulsifiers were contaminated more rapidly.

The reasoning for thinking this method was more sensitive was that the penetrant was more migratory and more likely to fill flaws when kept completely fluid and not allowed to lose volatile constituents by evaporation.

However, Sherwin showed that if the specimens are allowed to drain-dwell, the sensitivity is higher because the evaporation increases the dyestuff concentration of the penetrant on the specimen. As pointed-out in the section on penetrant materials, sensitivity increases as the dyestuff concentration increases.

Sherwin also cautions that the samples being inspected should be placed outside the penetrant tank wall so that vapors from the tank do not accumulate and dilute the dyestuff concentration of the penetrant on the specimen.

b. Penetrant Dwell Time: Penetrant **dwell time** is the total time that the penetrant is in contact with the part surface. The dwell time is important because it allows the penetrant the time necessary to seep or be drawn into a defect. Dwell times are usually recommended by the penetrant producers or required by the specification being followed. The time required to fill a flaw depends on a number of variables which include the following:

- The surface tension of the penetrant;
- The contact angle of the penetrant.

The dynamic shear viscosity of the penetrant, which can vary with the diameter of the capillary. The viscosity of a penetrant in micro capillary flaws is higher than its viscosity in bulk, which slows the infiltration of the tight flaws.

- The atmospheric pressure at the flaw opening;
- The capillary pressure at the flaw opening;
- The pressure of the gas trapped in the flaw by the penetrant;
- The radius of the flaw or the distance between the flaw walls;
- The density or specific gravity of the penetrant;
- Microstructural properties of the penetrant.

The ideal dwell time is often determined by experimentation and is often very specific to a particular application. For example, AMS 2647A requires that the dwell time for all aircraft and engine parts be at least 20 minutes, while ASTM E1209 only requires a five minute dwell time for parts made of titanium and other heat resistant alloys. Generally, there is no harm in using a longer penetrant dwell time as long as the penetrant is not allowed to dry.

c. Inspection of Liquid Penetrant: Unlike magnetic particle inspection, which can reveal subsurface defects, liquid penetrant inspection reveals only those defects that are open to the surface. Four groups of liquid penetrants are presently in use:

- **Group I**: Is a dye penetrant that is nonwater washable;
- **Group II**: Is a water washable dye penetrant;
- **Group III and Group IV**: Are fluorescent penetrants.

Carefully follow the instructions given for each type of penetrant since there are some differences in the procedures and safety precautions required for the various penetrants. Before using a liquid penetrant to inspect a weld, remove all slag, rust, paint, and moisture from the surface.

Except where a specific finish is required, it is not necessary to grind the weld surface as long as the weld surface meets applicable specifications. Ensure the weld contour blends into the base metal without under-cutting. When a specific finish is required, perform the liquid penetrant inspection before the finish is made. This enables you to detect defects that extend beyond he final dimensions, but you must make a final liquid penetrant inspection after the specified finish has been given.

Before using a liquid penetrant, clean the surface of the material very carefully, including the areas next tithe inspection area. You can clean the surface by swabbing it with a clean, free cloth saturated in a non-volatile solvent or by dipping the entire piece into a solvent. After the surface has been cleaned, remove all traces of the cleaning material. It is extremely important to remove all dirt, grease, scale, lint, salts, or other materials that would interfere with the inspection.

After the surface has dried, apply another substance, called a developer. Allow the developer (powder or liquid) to stay on the surface for a minimum of 7 minutes before starting the inspection. Leave it on no longer than 30 minutes, thus allowing a total of 23 minutes to evaluate the results.

The indications during a liquid penetrant inspection must be carefully interpreted and evaluated. In almost every inspection, some insignificant indications are present. Most of these are the result of the failure to remove the excess penetrant from the surface. At least 10 percent of all indications must be removed from the surface to determine whether defects are actually present or whether the indications are the result of excess penetrant.

12. Penetrant Removal Processes:

The penetrant removal procedure must effectively remove the penetrant from the surface of the part without removing an appreciable amount of entrapped penetrant from the defect. If the removal process extracts penetrant from the flaw, the flaw indication will be reduced by a proportional amount. If the penetrant is not effectively removed from the part surface, the contrast between the indication and the background will be reduced. Penetrant systems are classified into four methods of excess penetrant removal that include the following, just described above:

Method A: Water-Washable; Method B: Post-Emulsifiable, Lipophilic; Method C: Solvent Removable; Method D: Post-Emulsifiable, Hydrophilic. Of the **three** production penetrant inspection methods, the **Method A**, Water-Washable, is the most economical to apply. Water-washable or self-emulsifiable penetrants contain an emulsifier as an integral part of the formulation. Method C - Solvent Removable is used primarily for inspecting small localized areas. This method requires hand wiping the surface with a cloth moistened with the solvent remover, and is, therefore, too labor intensive for most production situations.

The excess penetrant may be removed from the object surface with a simple water rinse. These materials have the property of forming relatively viscous gels upon contact with water, which results in the formation of gel-like plugs in surface openings. While they are completely soluble in water, given enough contact time, the plugs offer a brief period of protection against rapid wash removal. Thus, water-washable penetrant systems provide ease of use and a high level of sensitivity.

When removal of the penetrant from the defect due to over-washing of the part is a concern, a post-emulsifiable penetrant system can be used. Post-emulsifiable penetrants require a separate emulsifier to breakdown the penetrant and make it water washable. The part is usually immersed in the emulsifier but hydrophilic emulsifiers may also be sprayed on the object. Spray application is not recommended for lipophilic emulsifiers because it can result in non-uniform emulsification if not properly applied.

Brushing of the emulsifier over the part **is not recommended** either because the bristles of the brush may force emulsifier into discontinuities, causing the entrapped penetrant to be removed. The emulsifier is allowed sufficient time to react with the penetrant on the surface of the part but not given time to make its way into defects to react with the trapped penetrant. The penetrant that has reacted with the emulsifier is easily cleaned away.

Controlling the reaction time is of essential importance when using a post-emulsifiable system. If the emulsification time is too short, an excessive amount of penetrant will be left on the surface, leading to high background levels. If the emulsification time is too long, the emulsifier will react with the penetrant entrapped in discontinuities, making it possible to deplete the amount needed to form an indication.

The **hydrophilic post-emulsifiable** method **(Method D)** is more sensitive than the **lipophilic post-emulsifiable** method **(Method B).** Since these methods are generally only used when very high sensitivity is needed, the hydrophilic method renders the lipophilic method virtually obsolete. The major advantage of hydrophilic emulsifiers is that they are less sensitive to variation in the contact and removal time.

While emulsification time should be controlled as closely as possible, a variation of one minute or more in the contact time will have little effect on flaw detectability when a hydrophilic emulsifier is used. On the contrary, a variation of as little as 15 to 30 seconds can have a significant effect when a lipophilic system is used. Using an emulsifier involves adding a couple of steps to the penetrant process, slightly increases the cost of an inspection.

When using an **emulsifier**, the penetrant process includes the **following steps** (extra steps in bold): 1. pre-clean part, 2. apply penetrant and allow to dwell, 3. pre-rinse to remove first layer of penetrant, 4. apply hydrophilic emulsifier and allow contact for specified time, 5. rinse to remove excess penetrant, 6. dry part, 7. apply developer and allow part to develop, and 8. inspect.

a. Rinse Method: The method used to rinse the excess from the object surface and time should be controlled to prevent over-washing. It is generally recommended that a coarse spray rinse or an air-agitated, immersion wash tank be used. When a spray is being used, it should be directed at a 45° angle to the part surface so as to not force water directly into any discontinuities that may be present. The spray or immersion time should be kept to a minimum through frequent inspections of the remaining background level.

b. Solvent Removable Penetrants: When a solvent removable penetrant is used, care must also be taken to carefully remove the penetrant from the part surface while removing as little as possible from the flaw. The first step in this cleaning procedure is to dry wipe the surface of the part in one direction using a white, lint-free, cotton rag. One dry pass in one direction is all that should be used to remove as much penetrant as possible. Next, the surface should be wiped with one pass in one direction with a rag moistened with cleaner.

One dry pass followed by one damp pass is all that is recommended. Additional wiping may sometimes be necessary; but keep in mind that with every additional wipe, some of the entrapped penetrant will be removed and inspection sensitivity will be reduced. To study the effects of the wiping process, Japanese researchers manufactured a test specimen out of acrylic plates that allowed them to view the movement of the penetrant in a narrow cavity.

The sample consisted of two pieces of acrylic with two thin sheets of vinyl clamped between as spaces. The plates were clamped in the corners and all but one of the edges sealed. The unsealed edge acted as the flaw. The clearance between the plates varied from 15 microns (0.059 inch) at the clamping points to 30 microns (0.118 inch) at the midpoint between the clamps. The distance between the clamping points was believed to be 30 mm (1.18 inch).

Although the size of the flaw represented by this specimen is large, an interesting observation was made. They found that when the surface of the specimen was wiped with a dry cloth, penetrant was blotted and removed from the flaw at the corner areas where the clearance between the plates was the least. When the penetrant at the side areas was removed, penetrant moved horizontally from the center area to the ends of the simulated crack where capillary forces are stronger.

Therefore, across the crack length, the penetrant surface has a parabola-like shape where the liquid is at the surface in the corners but depressed in the center. This shows that each time the cleaning cloth touches the edge of a crack, penetrant is lost from the defect. This also explains why the bleed out of an indication is often largest at the corners of cracks.

13. Use and Selection of a Developer:

The output from a **fluorescent penetrant** could be multiplied by up to **seven times** when a suitable powder developer was used. Another study showed that the use of developer can have a dramatic effect on the probability of detection (POD) of an inspection. When a Haynes Alloy 188, flat panel specimen with a low-cycle fatigue crack was inspected without a developer, a 90 % POD was never reached with crack lengths as long as 19 mm (0.75 inch). The operator detected only 86 of 284 cracks and had 70 false-calls.

When a developer was used, a 90 % POD was reached at 2 mm (0.077 inch), with the inspector identifying **277 of 311 cracks** with no false-calls. However, some authors have reported that in special situations, the use of a developer may actually reduce sensitivity. These situations primarily occur when large, well defined defects are being inspected on a surface that contains many no relevant indications that cause excessive bleed out.

a. Developer Application Method: Nonaqueous developers are generally recognized as the most sensitive when properly applied. There is less agreement on the performance of dry and aqueous wet developers, but the aqueous developers are usually considered more sensitive. Aqueous wet developers form a finer matrix of particles that is more in contact with the part surface. However, if the thickness of the coating becomes too great, defects can be masked.

Aqueous wet developers can cause leaching and blurring of indications when used with water-washable penetrants. The relative sensitivities of developers and application techniques as ranked in Volume II of the *Nondestructive Testing Handbook* are shown in the table below. There is general industry agreement with this table, but some industry experts feel that water suspendable developers are more sensitive than water-soluble developers. Sensitivity ranking of developers per the *Nondestructive Testing Handbook*:

Ranking	Developer Form	Method of Application
1	Nonaqueous, Wet Solvent	Spray
2	Plastic Film	Spray
3	Water-Soluble	Spray
4	Water-Suspendable	Spray
5	Water-Soluble	Immersion
6	Water-Suspendable	Immersion
7	Dry	Dust Cloud (Electrostatic)
8	Dry	Fluidized Bed
9	Dry	Dust Cloud (Air Agitation)
10	Dry	Immersion (Dip)

The following table lists the main **advantages and disadvantages** of the various developer types.

Developer	Advantages	Disadvantages
Dry:	Indications tend to remain brighter and more distinct over time. Easy to apply.	It does not form contrast background so cannot be used with visible systems. Difficult to assure entire part surface has been coated.
Soluble:	Ease of coating entire part. White coating for good contrast can be produced which work well for both visible and fluorescent systems.	Coating is translucent and provides poor contrast (not recommended for visual systems). Indications for water washable systems are dim and blurred.
Suspendable:	Ease of coating entire part indications are bright and sharp. White coating for good contrast can be produced which work well for both visible and fluorescent systems.	Indications weaken and become diffused after time.
Nonaqueous:	Easy to apply to readily accessible surfaces. White coating for good contrast can be produced which work well for both visible and fluorescent systems. Indications show-up rapidly and are well defined. Provides highest sensitivity.	Difficult to apply evenly to all surfaces. More difficult to clean part after inspection.

14. Control of Temperature:

The temperature of the penetrant materials and the part being inspected can have an effect on the results. Temperatures from 27 to 49°C (80 to 120°F) are reported in the literature to produce optimal results. Many specifications allow testing in the range of 4 to 52°C (40 to 125°F). A tip to remember is that surfaces that can be touched for an extended period of time without burning the skin are generally below 52°C (125°F).

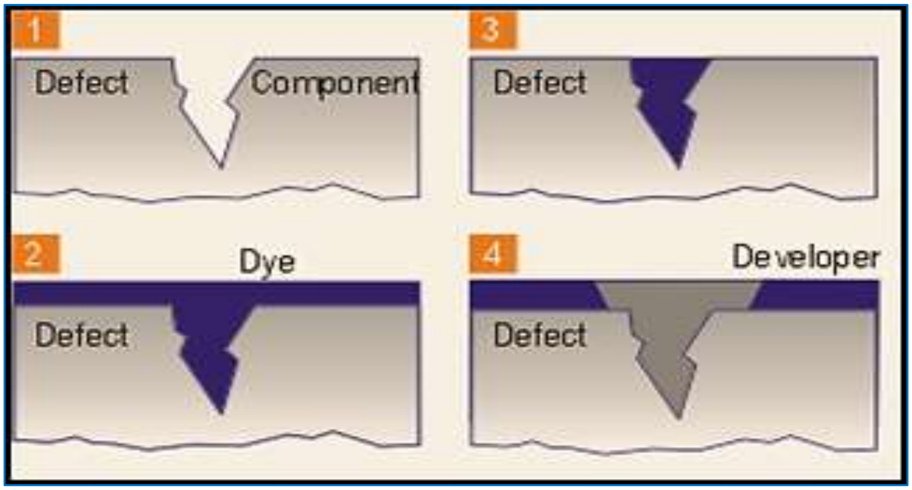
Since the surface tension of most materials decrease as the temperature increases, raising the temperature of the penetrant will increase the wetting of the surface and the capillary forces. Of course, the converse is also true, so lowering the temperature will have a negative effect on the flow characteristics. Raising the temperature will also raise the speed of evaporation of penetrants, which can have a positive or negative effect on sensitivity.

The impact will be positive if the evaporation serves to increase the dye concentration of the penetrant trapped in a flaw up to the concentration quenching point and not beyond. Higher temperatures and more rapid evaporation will have a negative effect if the dye concentration exceeds the concentration quenching point, or the flow characteristics are changed to the point where the penetrant does not readily flow.

The method of processing a hot part was once commonly employed. Parts were either heated or processed hot off the production line. In its day, this served to increase inspection sensitivity by increasing the viscosity of the penetrant. However, the penetrant materials used today have 1/2 to 1/3 the viscosity of the penetrants on the market in the 1960's and 1970's. Heating the part prior to inspection is no longer necessary and no longer recommended.

15. Convenience of the Penetrant Application:

The application of the penetrant is the step of the process that requires the least amount of control. As long as the surface being inspected receives a generous coating of penetrant, it really doesn't matter how the penetrant is applied. Generally, the application method is an economic or convenience decision. It is important that the part be thoroughly cleaned and dried. Any contaminates or moisture on the surface of the part or within a flaw can prevent the penetrant material from entering the defect. The part should also be cool to the touch. The recommended range of temperature is 4 to 52°C (39 to 125°F).



The water washable penetrants must be checked regularly. Water-based, water washable penetrants are checked with a refractometer. The rejection criteria is different for different penetrants, so the requirements of the qualifying specification or the manufacturer's instructions must be consulted. Non-water-based, water washable penetrants are checked using the procedure specified in ASTM D95 or ASTM E 1417.

16. Quality Control of Drying Process:

The temperature used to **dry parts** after the application of an **aqueous wet developer** or prior to the application of a **dry powder** or a nonaqueous wet developer, must be controlled to prevent "cooking" of the penetrant in the defect. High drying temperature can affect penetrants in a couple of ways. **First**, some penetrants can fade at high temperatures due to dye vaporization or sublimation.

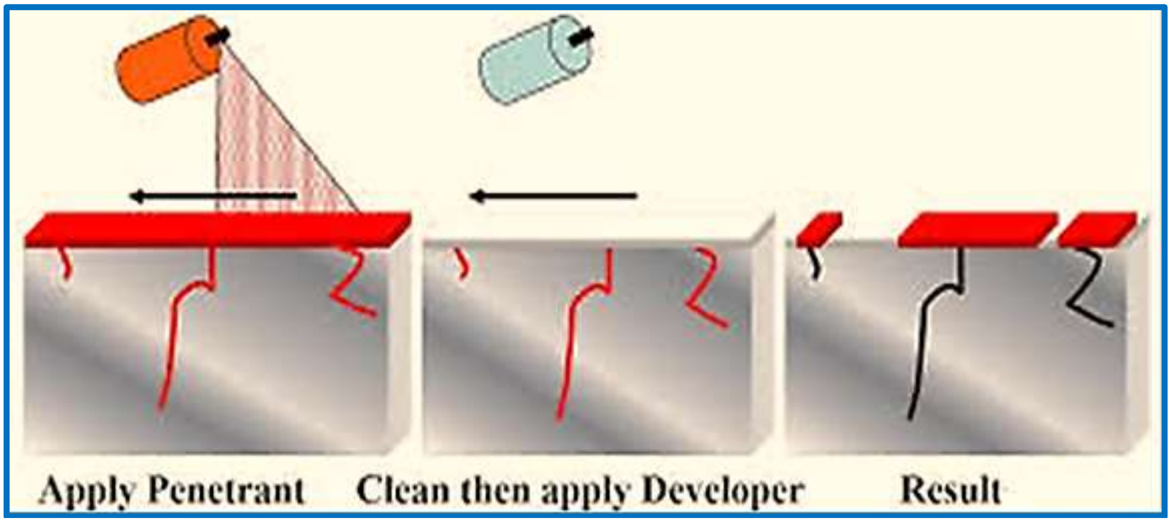
Second, high temperatures can cause the penetrant to dry in the flaw, preventing it from migrating to the surface to produce an indication. Thus, to prevent harming the penetrant material, drying temperature should be kept to under 71°C. The drying should be limited to the minimum length of time necessary to thoroughly dry the component being inspected.

17. Dry Powder Developer:

A dry powder developer should be checked daily to ensure that it is fluffy and not caked. It should be similar to fresh powdered sugar and not granulated like powdered soap. It should also be relatively free from specks of fluorescent penetrant material from previous inspection. This check is performed by spreading a sample of the developer out and examining it under UV light. If there are ten or more fluorescent specks in a 10 cm diameter area, the batch should be discarded. Apply a light coat of the developer by immersing the test component or dusting the surface. After the development time, excessive powder can be removed by gently blowing on the surface with air not exceeding 35 kPa or 5 psi.

18. Wet Soluble Developer:

Wet **soluble developer** must be completely **dissolved in the water** and wet **suspendable developer** must be **thoroughly mixed** prior to application. The concentration of powder in the carrier solution must be controlled in these developers. The concentration should be checked at least weekly using a hydrometer to make sure it meets the manufacturer's specification.



To check for contamination, the solution should be examined weekly using both white light and UV light. If a scum is present or the solution fluoresces, it should be replaced. Some specifications require that a clean aluminum panel be dipped in the developer, dried, and examined for indications of contamination by fluorescent penetrant materials.

These developers are applied immediately after the final wash. A uniform coating should be applied by spraying, flowing or immersing the component. They should never be applied with a brush. Care should be taken to avoid a heavy accumulation of the developer solution in crevices and recesses. Prolonged contact of the component with the developer solution should be avoided in order to minimize dilution or removal of the penetrant from discontinuities.

a. Development Time: Minimum of **10 minutes** and no more than **2 hours** before inspecting, applied to all **non-ferrous materials and ferrous** materials. Magnetic Particle inspection is often used for ferrous materials due its subsurface detection capability. LPI is used to detect casting, forging and welding surface defects such as hairline cracks, surface porosity, leaks in new products, and fatigue cracks on in-service components.

b. Nature of the Defect: The nature of the defect can have a large effect on sensitivity of a liquid penetrant inspection. Sensitivity is defined as the smallest defect that can be detected with a high degree of reliability. Typically, the crack length at the sample surface is used to define size of the defect. A survey of any probability-of-detection curve for penetrant inspection will quickly lead one to the conclusion that crack length has a definite effect on sensitivity.

In general, penetrant inspections are more effective at finding **small** round defects than small linear defects. Small round defects are generally easier to detect for several reasons. First, they are typically volumetric defects that can trap significant amounts of penetrant. Second, round defects fill with penetrant faster than linear defects. One research effort found that elliptical flaw with length to width ratio of 100, will take the penetrant nearly 10 times longer to fill than a cylindrical flaw with the same volume.

However, the **crack length** alone does not determine whether a flaw will be seen or go undetected. The volume of the defect is likely to be the more important feature. The flaw must be of sufficient volume so that enough penetrant will bleed back out to a size that is detectable by the eye or that will satisfy the dimensional thresholds of fluorescence. The studies about this subject are:

- **Deeper flaws than shallow flaws:** Deeper flaws will trap more penetrant than shallow flaws, and they are less prone to over washing.

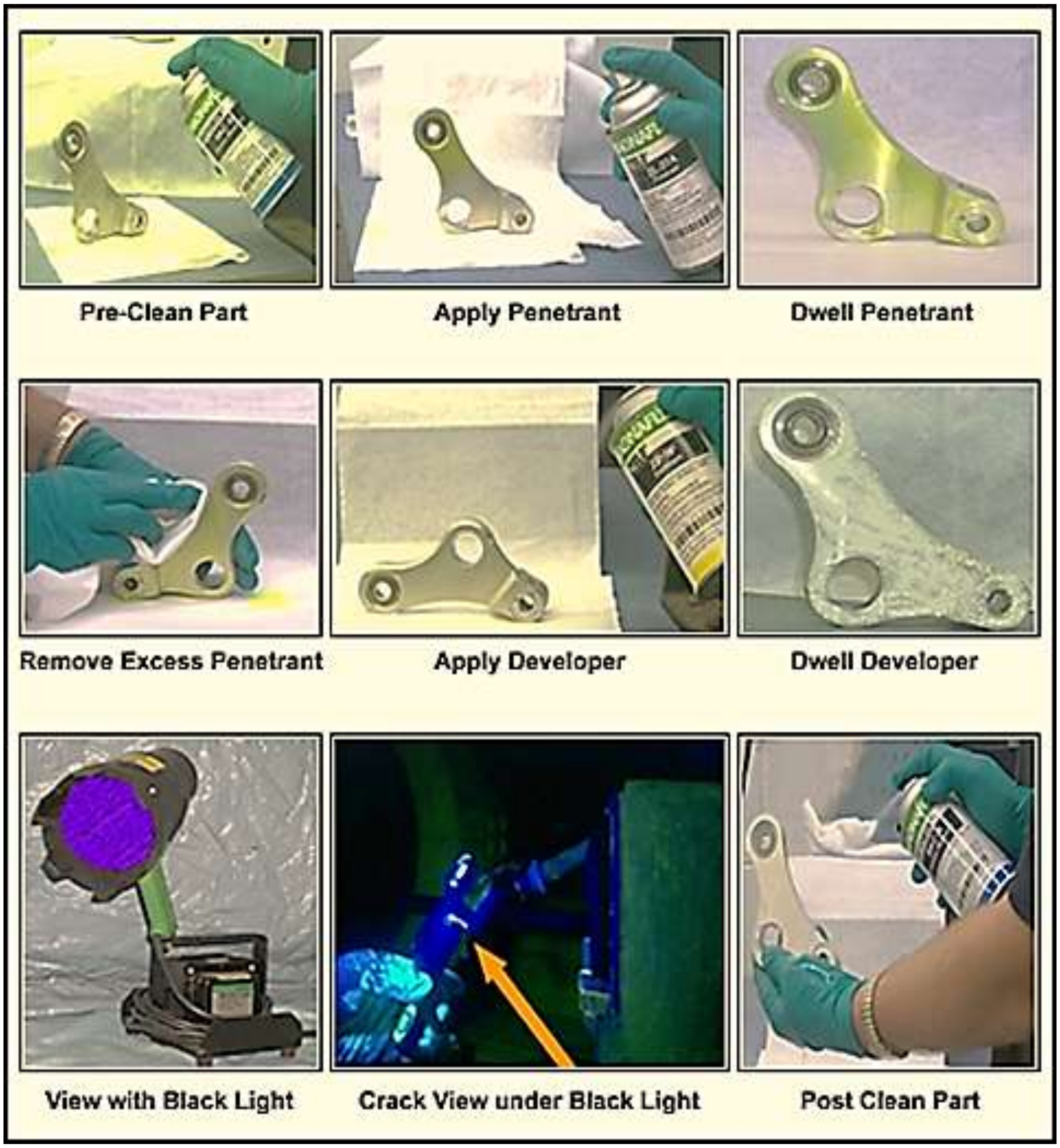
- **Flaws with a narrow opening at the surface than wide open flaws:** Flaws with narrow surface openings are less prone to over washing.

- **Flaws on smooth surfaces than on rough surfaces:** The surface roughness primarily affects the removability of a penetrant. Rough surfaces tend to trap more penetrant in the various tool marks, scratches, and pits that make up the surface: Removing the penetrant from the surface of the part is more difficult and a higher level of background fluorescence or over washing may occur.

- **Flaws with rough fracture surfaces than smooth fracture surfaces:** The surface roughness that the fracture faces is a factor in the speed at which a penetrant enters a defect. In general, the penetrant spreads faster over a surface as the surface roughness increases. It should be noted that a particular penetrant may spread slower than others on a smooth surface but faster than the rest on a rougher surface.

- **Flaws under tensile or no loading than flaws under compression loading:** In 1987, the University College London evaluated the effect of crack closure on detectability. Researchers used a four-point bend fixture to place tension and compression loads on specimens that were fabricated to contain fatigue cracks. All cracks were detected with no load and with tensile loads placed on the parts. However, as compressive loads were placed on the parts, the crack length steadily decreased as load increased until a load was reached when the crack was no longer detectable.

19. Practical Examples:

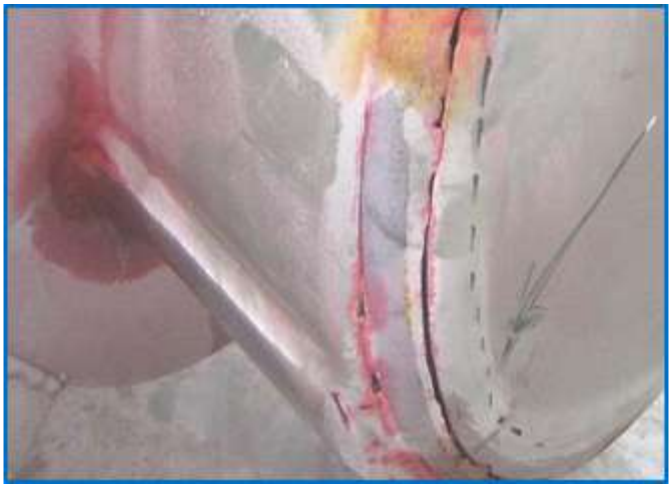


Pipe - LP Inspection

Screw - LP Inspection

Forging - LP Inspection

Casting - LP Inspection



Pressure Vessel Welding – LP Inspection

Non-ferrous Materials – LP Inspection

Welding - LP Inspection

Obs.: The pieces are coated with a special solution that contains a visible (or fluorescent) dye with good penetrating ability. Excess solution is then removed from the surface of the object, but leaving it in surface breaking defects. A developer, which also acts as a white contrast background, is then applied to draw the penetrant out of the defects. Techniques differ when no developer is required, as ultraviolet light is used to make the bleed-out fluoresce brightly, thus allowing imperfections to be readily seen.

3. Magnetic Particle Inspection (MT):

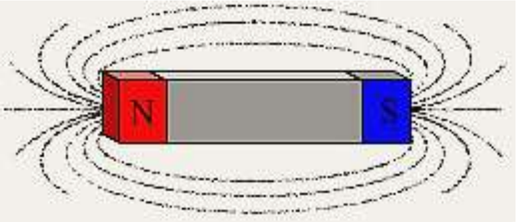
Magnetic particle inspection (MPI) is a nondestructive testing method used for defect detection. MPI is fast and relatively easy to apply, and part surface preparation is not as critical as it is for some other NDT methods. These characteristics make MPI one of the most widely utilized nondestructive testing methods.

MPI uses **magnetic fields** and small magnetic particles (i.e. Iron filings) to detect flaws in components. The only requirement from an inspectable 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.

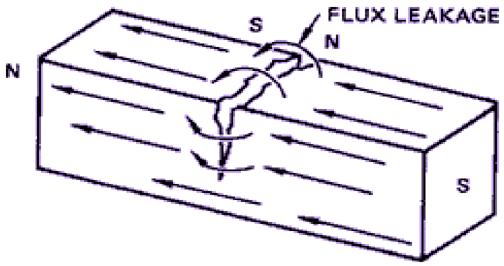
The method is used to inspect a variety of product forms including **castings, forgings, and weldments**. Many different industries use magnetic particle inspection for determining a component's fitness-for-use. Some examples of industries that use magnetic particle inspection are the structural steel, automotive, petrochemical, power generation, and aerospace industries. **Underwater inspection** is another area where magnetic particle inspection is used to test offshore structures and **underwater pipelines**.

1. Basic Principles:

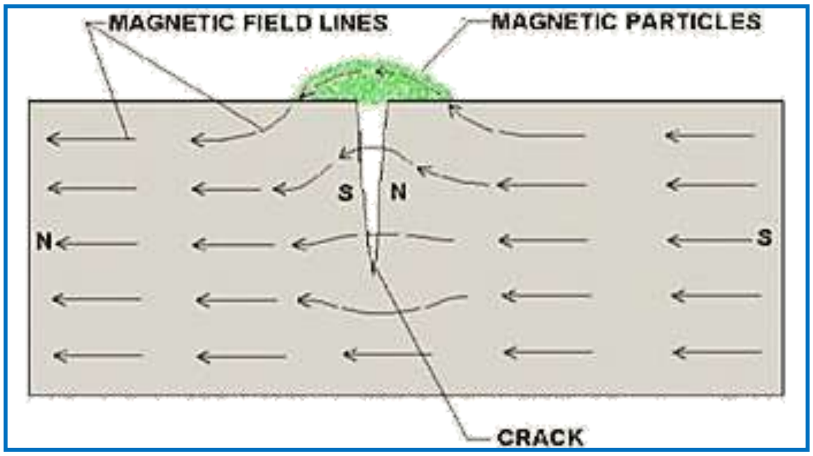
In theory, magnetic particle inspection (MPI) is a relatively simple concept. It can be considered as a combination of two nondestructive testing methods: magnetic flux leakage testing and visual testing. Consider the case of a bar magnet. It has a magnetic field in and around the magnet. Any place that 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. When a bar magnet is broken in the center of its length, 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**. When **iron particles** are sprinkled on a **cracked piece**, the particles are attracted and crowded not only at the ends of the magnetic pole, but also at the poles at the **edges of the crack**. This agglomerate of particles is much easier to see than the actual crack, and then this is the basic principle for magnetic particle inspection.



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. History of Magnetic Particle Inspection:

Magnetism is the ability of matter to attract other matter to it. The ancient Greeks were the first to discover this phenomenon in a mineral they named magnetite. Later on Bergmann, Becquerel, and Faraday discovered that all matter including liquids and gasses were affected by magnetism, but only a few responded to a noticeable extent.

The earliest known use of magnetism to inspect an object took place as early as 1868. **Cannon** barrels were checked for defects by magnetizing the barrel then sliding a magnetic compass along the barrel's length. These early inspectors were able to locate flaws in the barrels by monitoring the needle of the compass. This was a form of nondestructive testing but the term was not commonly used until sometime after World War I.

In the early 1920’s, **William Hooke** realized that magnetic particles (colored metal shavings) could be used with magnetism as a means of locating defects. Hooke discovered that a surface or subsurface flaw in a magnetized material caused the magnetic field to distort and extend beyond the part. This discovery was brought to his attention in the machine shop.

He noticed that the metallic grindings from hard steel parts (held by a magnetic chuck while being ground) formed patterns on the face of the parts which corresponded to the cracks in the surface. Applying a fine ferromagnetic powder to the parts caused a buildup of powder over flaws and formed a visible indication. The image shows a 1928 Electro-Magnetic Steel Testing Device (MPI) made by the Equipment and Engineering Company Ltd. (ECO) of Strand, England.

In the early 1930’s, magnetic particle inspection was quickly **replacing** the oil-and-whiting method (an early form of the liquid penetrant inspection), as the method of choice by the railroad industry to inspect steam engine boilers, wheels, axles, and tracks. Today, the MPI inspection method is used extensively to check for flaws in a large variety of manufactured materials and components. MPI is used to check materials such as steel bar stock for seams and other flaws prior to investing machining time during the manufacturing of a component.

Critical **automotive** components are inspected for flaws after fabrication to ensure that defective parts are not placed into service. MPI is used to inspect some highly loaded components that have been in-service for a period of time. For example, many components of high performance racecars are inspected whenever the engine, drive train or another system undergoes an overhaul. MPI is also used to evaluate the integrity of structural welds on bridges, storage tanks, and other safety critical structures.

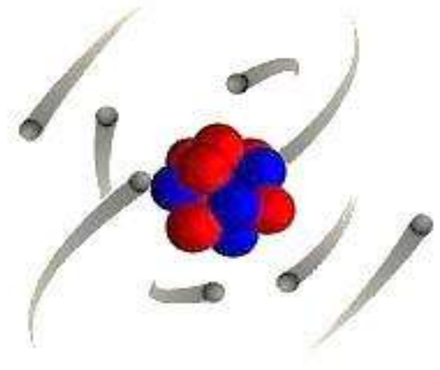
3. Magnetism Principles:

Magnets are very common items in the workplace and household. Uses of magnets range from holding pictures on the refrigerator to causing torque in electric motors. Most people are familiar with the general properties of magnets but are less familiar with the source of magnetism. The traditional concept of magnetism centers around the magnetic field and what is known as a dipole.

The term "magnetic field" simply describes a volume of space where there is a change in energy within that volume. This change in energy can be detected and measured. The location where a magnetic field can be detected exiting or entering a material is called a magnetic pole. Magnetic poles have never been detected in isolation but always occur in pairs, hence the name dipole. Therefore, a dipole is an object that has a magnetic pole on one end and a second, equal but opposite, magnetic pole on the other.

A bar magnet can be considered a dipole with a north pole at one end and south pole at the other. A magnetic field can be measured leaving the dipole at the north pole and returning the magnet at the south pole. If a magnet is cut in two, two magnets or dipoles are created out of one. This sectioning and creation of dipoles can continue to the atomic level. Therefore, the source of magnetism falls in the basic building block of all matter...the atom.

a. The Source of Magnetism: All matter is composed of atoms, and atoms are composed of protons, neutrons and electrons. The protons and neutrons are located in the atom's nucleus and the electrons are in constant motion around the nucleus. Electrons carry a negative electrical charge and produce a magnetic field as they move through space. A magnetic field is produced whenever an electrical charge is in motion. The strength of this field is called the magnetic moment.



This may be hard to visualize on a subatomic scale but consider electric current flowing through a conductor. When the electrons (electric current), are flowing through a conductor, a magnetic field forms around the conductor. This magnetic field can be detected using a compass. The magnetic field will place a force on the compass needle, which is another example of a dipole. Since all matter is comprised of atoms, all materials are affected in some way by a magnetic field. However, not all materials react the same way.

b. Magnetic Materials Classification: 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 motion, the change in 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.

- **Diamagnetic:** Materials have a **weak, 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. In diamagnetic materials all the electron are paired so there is no permanent net magnetic moment per atom. Diamagnetic properties arise from the realignment of the electron paths under the influence of an external magnetic field. Most elements in the periodic table, including copper, silver, and gold, are diamagnetic.

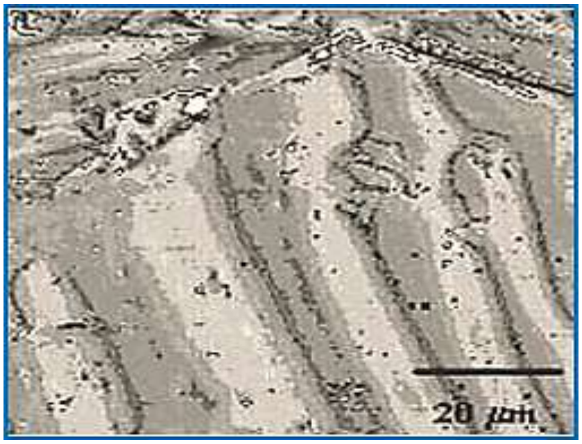
- **Paramagnetic:** Materials have a **small, positive susceptibility** to magnetic fields. These materials are slightly attracted by a magnetic field and the material does not retain the magnetic properties when the external field is removed. Paramagnetic properties are due to the presence of some unpaired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

- **Ferromagnetic:** Materials have a **large, 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 **unmagnetized state**, the properties 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.

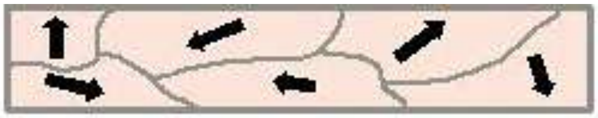
During solidification, a trillion or more atom moments are aligned parallel so that the magnetic force within the domain is strong in one direction. Ferromagnetic materials are said to be characterized by "spontaneous magnetization" since they obtain saturation magnetization in each of the domains without 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.

c. Magnetic Properties: 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. The magnetic properties can be detected using **Magnetic Force Microscopy (MFM)** and images of the domains, as shown below.

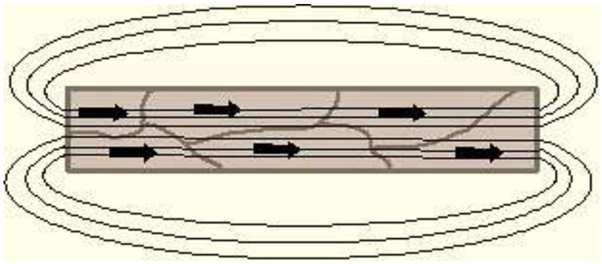


Magnetic Force Microscopy (MFM) image showing the magnetic properties in a piece of heat treated carbon steel.

Ferromagnetic materials become magnetized when the magnetic domains within the material are aligned. 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.

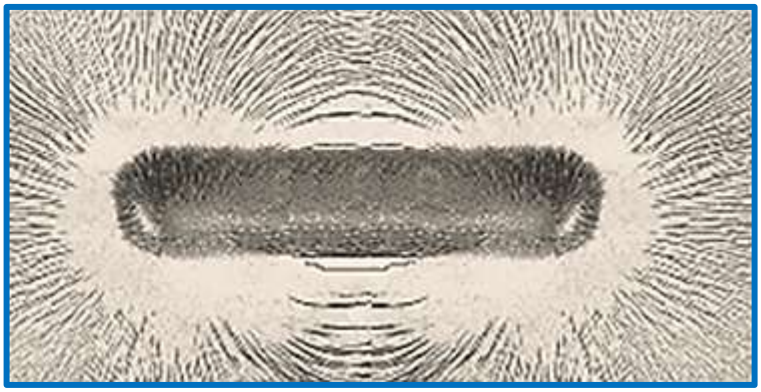


Unmagnetized Material



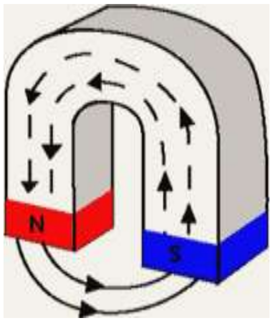
Magnetized Material

d. Magnetic Field Around a Bar Magnet: The 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**. 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.



Obs.: Thus, 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.

e. Magnetic Fields Around a 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. 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.



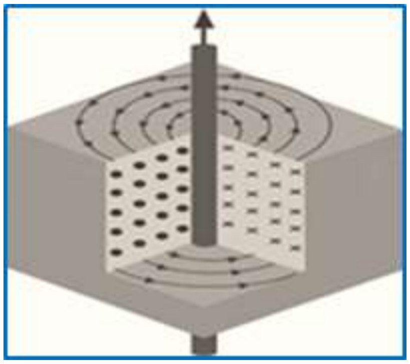
If a bar magnet was placed across the end of a **horseshoe magnet** or if a magnet was formed in the shape of a ring, the lines of magnetic force would not even need to enter the air. The value of such a magnet where the magnetic field is completely contained with the material probably has limited use.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

4. General Properties of Magnetic Lines:

Magnetic lines have a number of important properties, which include:

1. Magnetic lines 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;
2. Magnetic lines never cross one another;
3. Magnetic lines all have the same strength;
4. Magnetic lines density decreases (they spread out) when they move from an area of higher permeability to an area of lower permeability;
5. Magnetic lines density decreases with increasing distance from the poles;
6. Magnetic lines are considered to have direction as if flowing, though no actual movement occurs;
7. Magnetic lines flow from south pole to north pole within a material and north pole to south pole in air.

a. 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.

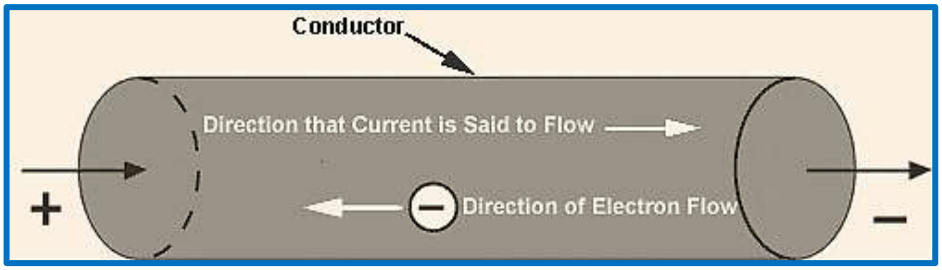


Hans Oersted studied the nature of the magnetic field around the long straight wire. He found that the magnetic field existed in circular form around the wire and that the intensity of the field was directly proportional to the amount of current carried by the wire. He also found that the strength of the field was strongest next to the wire and diminished with distance from the conductor until it could no longer be detected.

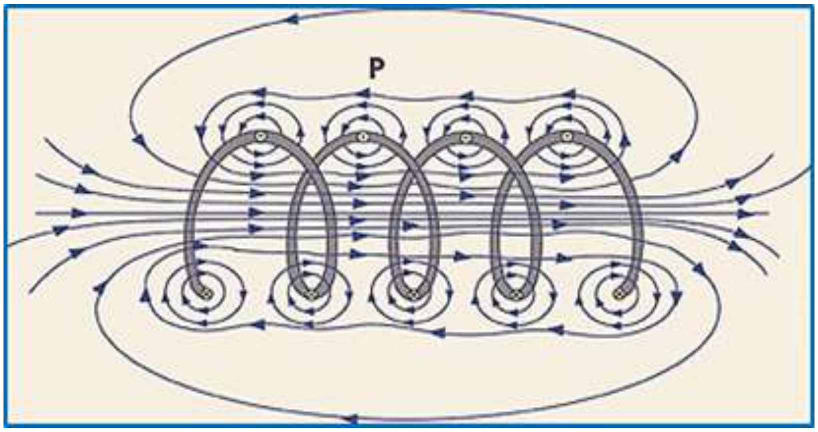
In most conductors, the magnetic field exists only as long as the current is flowing (i.e. an electrical charge is in motion). However, in ferromagnetic materials the electric current will cause some or all of the magnetic domains to align and a residual magnetic field will remain. Oersted also noticed 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 above. There is a simple rule for remembering the direction of the magnetic field around a conductor. It is called the **right-hand clasp 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.

b. Right-hand Clasp Rule: For the right-hand rule **to work**, one important thing that must be remembered about the **direction** of current flow. Standard convention has current flowing from the **positive terminal** to the **negative terminal**. This convention is credited to **Benjamin Franklin** who theorized that electric current was due to a positive charge moving from the positive terminal to the negative terminal. However, it was later discovered that the movement of the negative charged electron, is responsible for electrical current. However, Franklin's convention is still used today.



c. Magnetic Field of 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. 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.

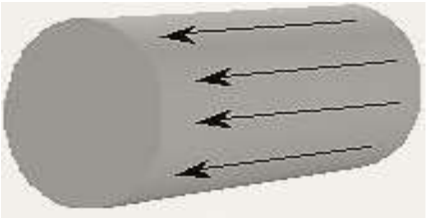


The strength of a **coil's magnetic field** increases not only with increasing current, but also with each loop that is added to the coil. A long, straight coil of wire is called a solenoid and can be used to generate a nearly uniform magnetic field similar to that of a bar magnet. The concentrated magnetic 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.

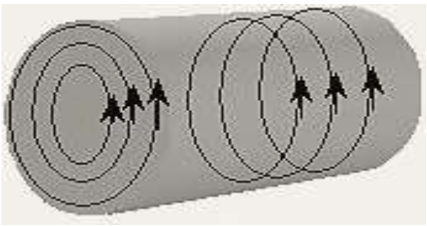
5. Magnetic Flaw Detectability:

To properly inspect a component for cracks or other defects, it is important to understand that the orientation between the **magnetic lines** and the flaw is very important. There are **two** general types of magnetic fields that can be established within a component.

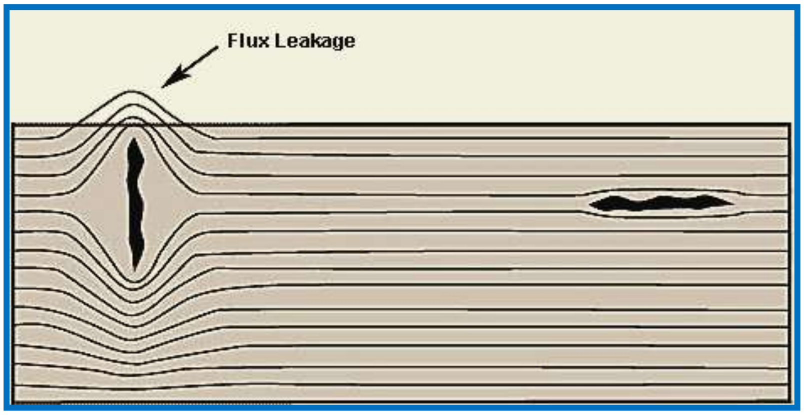
- **Longitudinal magnetic field**: Has magnetic lines that run parallel to the long axis of the part. Longitudinal magnetization of a component can be accomplished using the longitudinal field set up by a coil or solenoid. It can also be accomplished using permanent magnets or electromagnets.



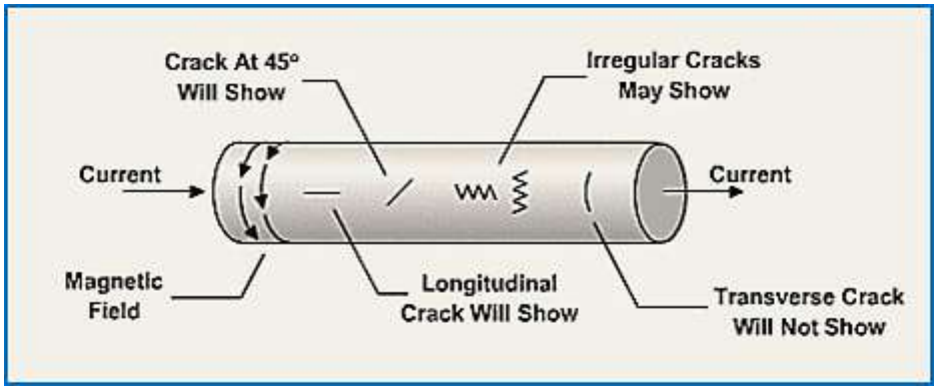
- **Circular magnetic field**: Has magnetic lines that run circumferentially around the perimeter of a part. A circular magnetic field is induced in an article by either passing current through the component or by passing current through a conductor surrounded by the component.



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.



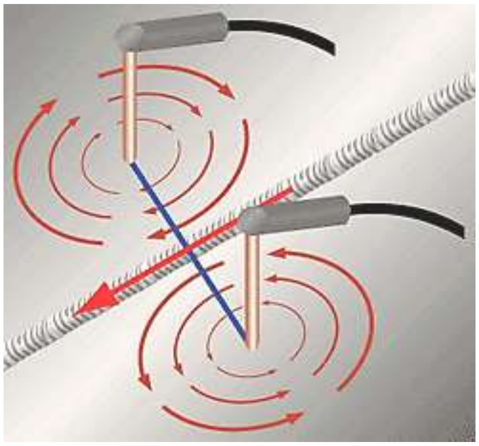
An orientation of **45 to 90 degrees** between the magnetic field and the defect is necessary to form an indication. Since defects may occur in various and unknown directions, each part is normally magnetized in two directions at right angles to each other. If the component below is considered, it is 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.



6. 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. 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.

a. 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.

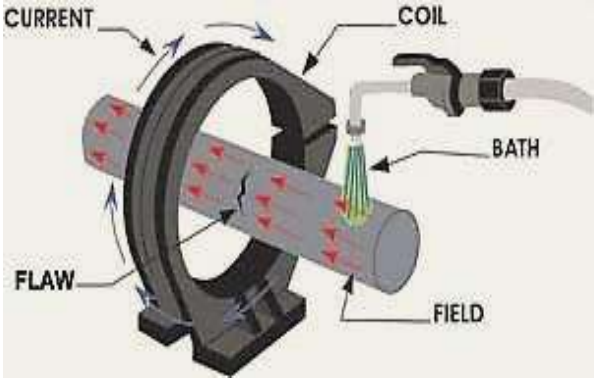


There are several ways that direct magnetization is commonly accomplished. One way involves clamping the component between two electrical contacts in a special piece of equipment. Current is passed through the component and a circular magnetic field is established in and around the component.

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

b. 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.

c. Electromagnets: in the form of an adjustable horseshoe magnet (called a yoke) 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.

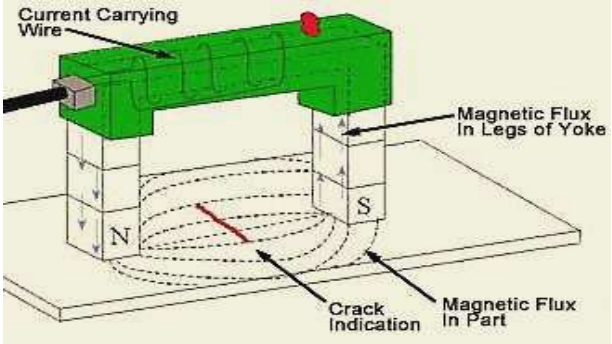


A circular magnetic field can be established in cylindrical components by using a **central conductor.** Typically, one or more cylindrical components are hung from a solid copper bar running through the inside diameter. Current is passed through the copper bar and the resulting circular magnetic field establishes a magnetic field within the test components.

The use of **coils** and **solenoids** is a third method of indirect magnetization. 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."

7. Magnetizing Current:

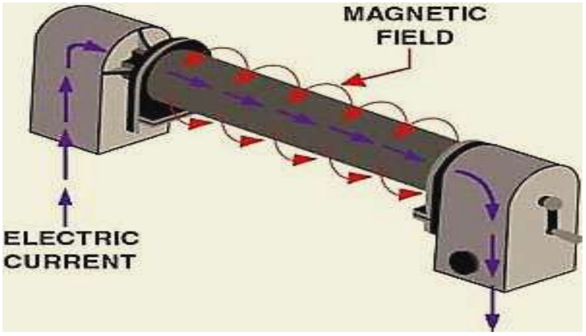
Electric current is often used to establish the magnetic field in components during magnetic particle inspection. Alternating current and direct current are the two basic types of current commonly used. Current from single phase 110 volts, to three phase 440 volts, are used when generating an electric field in a component. Current flow is often modified to provide the appropriate field within the part.

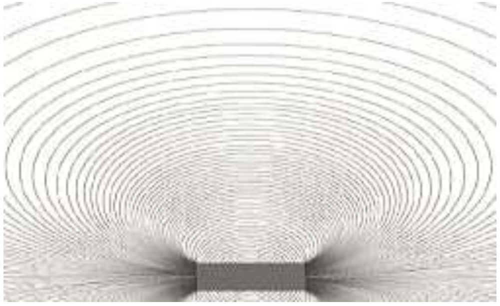


a. Direct Current: Direct current (DC) flows continuously in one direction at a constant voltage. A battery is the most common source of direct current. Direct current is said to flow from the positive to the negative terminal. Actually, it is known that the electrons flow in the opposite direction.

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.

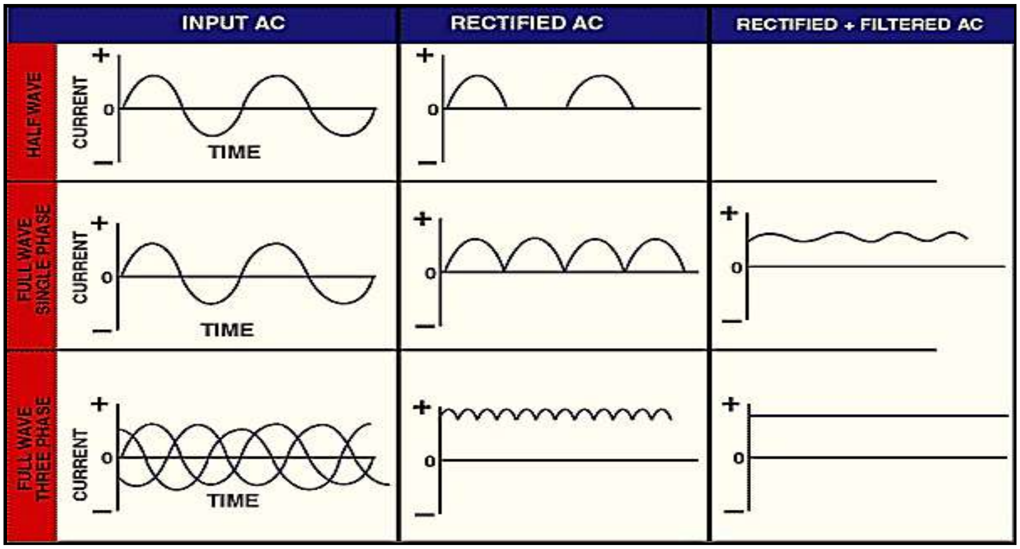
b. Alternating Current: Alternating current (AC) reverses in direction at a rate of 50 or 60 cycles per second. In the United States, 60 Hz current is the commercial norm but 50 Hz current is common in many countries. Since AC is readily available in most facilities, it is convenient to make use of it for magnetic particle inspection. However, when AC is used to induce a magnetic field in ferromagnetic materials the magnetic field will be limited to a narrow region at the component surface.





This phenomenon is known as the "**skin effect**" and occurs because the changing magnetic field generates eddy currents in the test object. The eddy currents produce a magnetic field that opposes the primary field, thus reducing the net magnetic flux below the surface. Therefore, it is recommended that AC be used only when the inspection is limited to surface defects.

c. 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.



d. Half Wave Rectified Alternating Current (HWAC): When single phase alternating current is passed through a rectifier, current is allowed to flow in only one direction. The reverse half of each cycle is blocked out so that a one directional, pulsating current is produced. The current rises from zero to a maximum and then returns to zero. No current flows during the time when the reverse cycle is blocked out. The HWAC repeats at same rate as the un-rectified current (60 hertz typical). Since half of the current is blocked out, the amperage is half of the unaltered AC.

This type of current is often referred to as half wave DC or pulsating DC. The pulsation of the HWAC helps magnetic particle indications form by vibrating the particles and giving them added mobility. This added mobility is especially important when using dry particles. The pulsation is reported to significantly improve inspection sensitivity. HWAC is most often used to power electromagnetic yokes.

e. Full Wave Rectified Alternating Current (FWAC) (Single Phase): Full wave rectification inverts the negative current to positive current rather than blocking it out. This produces a pulsating DC with no interval between the pulses. Filtering is usually performed to soften the sharp polarity switching in the rectified current. While particle mobility is not as good as half-wave AC due to the reduction in pulsation, the depth of the subsurface magnetic field is improved.

f. Three Phase Full Wave Rectified Alternating Current: Three phase current is often used to power industrial equipment because it has more favorable power transmission and line loading characteristics. This type of electrical current is also highly desirable for magnetic particle testing because when it is rectified and filtered, the resulting current very closely resembles direct current. Stationary magnetic particle equipment wired with three phase AC will usually have the ability to magnetize with AC or DC (three phase full wave rectified), providing the inspector with the advantages of each current form.

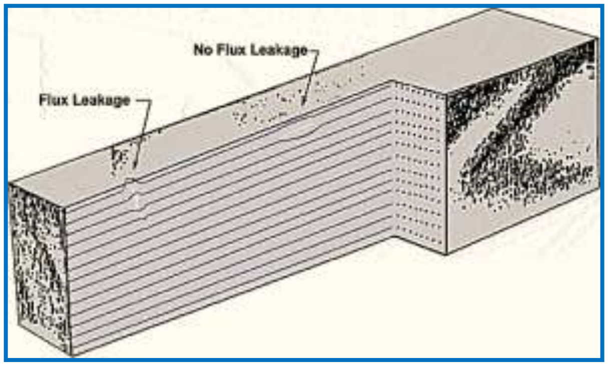
8. Longitudinal Magnetic Fields:

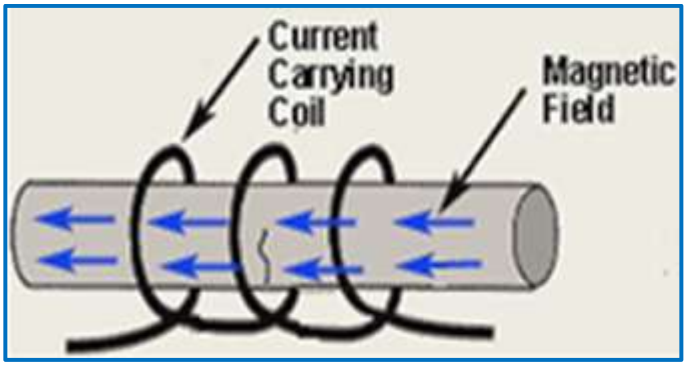
When the length of a component is several times larger than its diameter, a longitudinal magnetic field can be established in the component. The component is often placed longitudinally in the concentrated magnetic field that fills the center of a coil or solenoid. This magnetization technique is often referred to as a "coil shot." 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 are much denser inside the ferromagnetic material than in air because ferromagnetic materials have much higher **permeability than 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 cannot 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.

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.

When a component with considerable length is **magnetized** using a **solenoid**, it is possible to magnetize only a portion of the component. 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 an opposite pole on the other side of the solenoid.





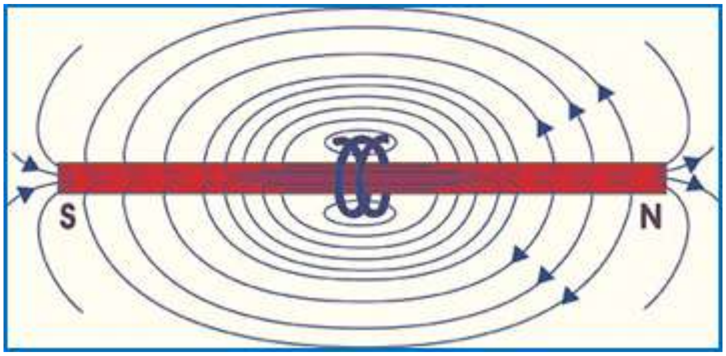
This occurs because the magnetizing force diminishes with increasing distance from the solenoid. As a result, the magnetizing force may only be strong enough to align the magnetic domains within and very near the solenoid. The unmagnetized portion of the component will not support as much magnetic flux 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.

9. Circular Magnetic Fields:

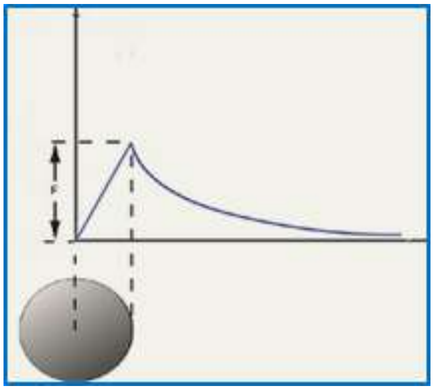
When an electric current is passed through a solid conductor, a magnetic field forms in and around the conductor. The following statements can be made about the distribution and intensity of the magnetic field. The field strength varies from zero at the center of the component to a maximum at the surface. The field strength outside the conductor decreases with distance from the conductor.

- 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.)

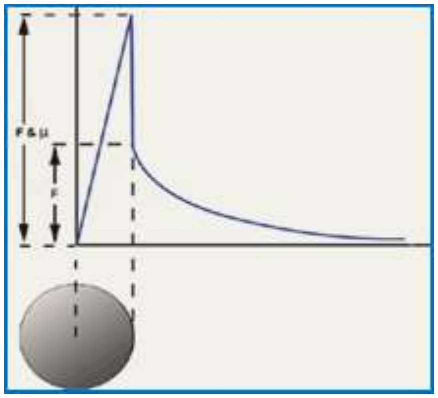
- The field strength outside the conductor is directly proportional to the current strength. Inside the conductor, the field strength is dependent on the current strength, magnetic permeability of the material, and if magnetic, the locations on the B-H curve.



In the images below, 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 is in the nonmagnetic conductor. This is due to the permeability of the magnetic material.



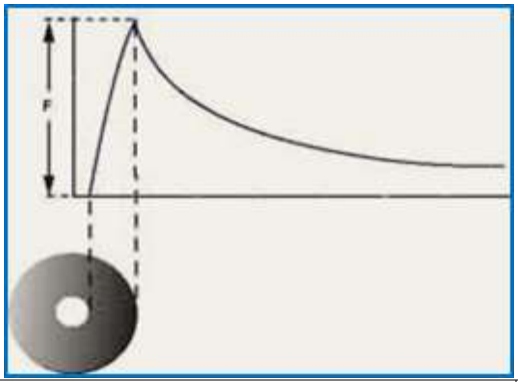
The magnetic field distribution in and around a solid conductor of a nonmagnetic material carrying **direct current**.



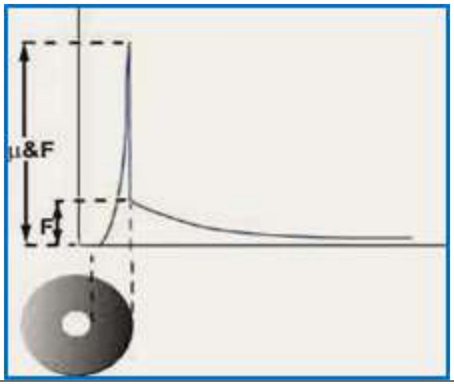
The magnetic field distribution in and around a solid conductor of a magnetic material carrying **direct current**.

When the conductor is carrying alternating current, the internal magnetic field strength rises from zero at the center to a maximum at the surface. 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. 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. 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. 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.



The magnetic field distribution in and around a hollow conductor of a nonmagnetic material carrying **direct current**.



The magnetic field distribution in and around a hollow conductor of a magnetic material carrying **alternating current.**

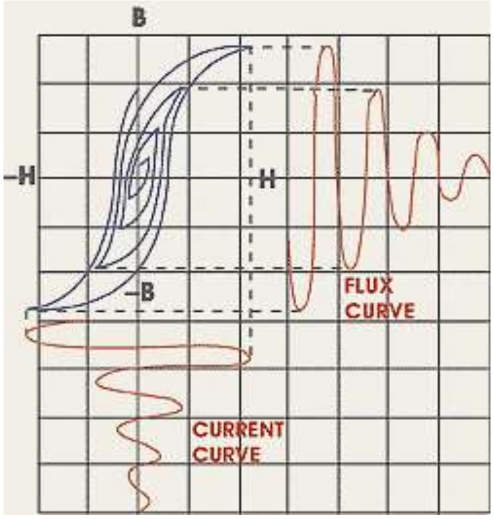
When AC is passed through a hollow circular conductor, the skin effect concentrates the field strength at the inside surface of hollow conductor is very low when a circular magnetic field was established by direct magnetization. Therefore, the direct method of magnetization is not recommended when inspecting the inside diameter wall of a hollow component for shallow defects. The field strength increases rapidly as one moves out (into the material) from the ID, so if the defect has significant depth, it may be detectable.

However, a much better method of magnetizing hollow components for inspection of the ID and OD surfaces is with the use of a central conductor. As can be seen in the field distribution image to the right, when current is passed through a nonmagnetic central conductor (copper bar), the magnetic field produced on the inside diameter surface of a magnetic tube is much greater and the field is still strong enough for defect detection on the OD surface.

10. Demagnetization:

After conducting a magnetic particle inspection, it is usually necessary to demagnetize the component. Reminiscent magnetic fields can, affect machining by causing cuttings to cling to a component, interfere with electronic equipment such as a compass, 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, cause abrasive particles to cling to bearing or faying surfaces and increase wear.

Removal of a field 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 its 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.

A field meter is often used to verify that the residual flux has been removed from a component. Industry standards usually require that the magnetic flux be reduced to less than 3 gauss after.

11. Measuring Magnetic Fields:

When performing a magnetic particle inspection, it is very important to be able to determine the direction and intensity of the magnetic field. As described previously, the direction of the magnetic field should be between **45 and 90 degrees** to the longest dimension of the **flaw** for best detectability. The field intensity must be high enough to cause an indication to form, but not too high to cause non-relevant indications to mask relevant indications.

To cause an indication to form, the field strength in the object must produce a flux leakage field that is strong enough to hold the magnetic particles in place over a discontinuity. Flux measurement devices can provide important information about the field strength. Since it is impractical to measure the actual field strength within the material, all the devices measure the magnetic field that is outside of the material.

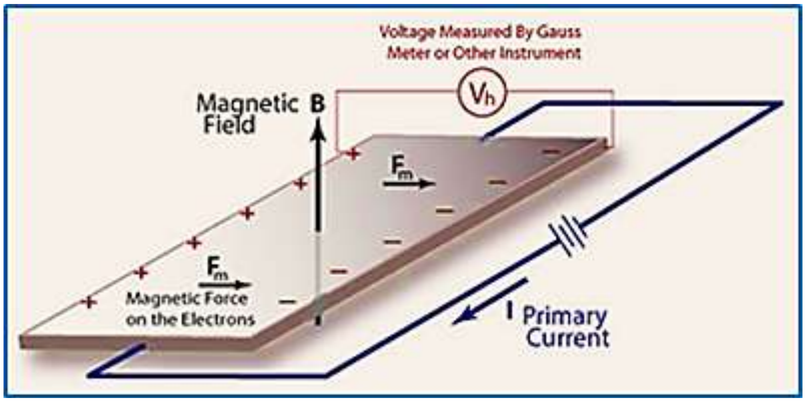
There are a number of different devices that can be used to detect and measure an external magnetic field. The two devices commonly used in magnetic particle inspection are the field indicator and the Hall-effect meter, which is also called a gauss meter. Pie gauges and shims are devices that are often used to provide an indication of the field direction and strength but do not actually yield a quantitative measure.

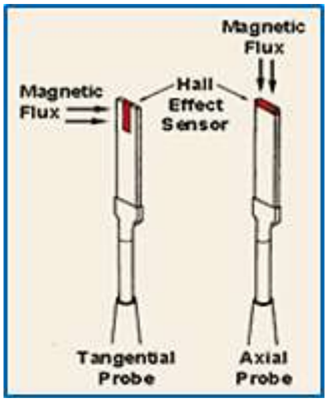
12. Field Indicators:

Field indicators are small mechanical devices that utilize a soft iron vane that is deflected by a magnetic field. The X-ray image below shows the inside working of a field meter looking in from the side. The vane is attached to a needle that rotates and moves the pointer for the scale. Field indicators can be adjusted and calibrated so that quantitative information can be obtained. However, the measurement range of field indicators is usually small due to the mechanics of the device. The one shown to the right has a range from plus 20 gauss to minus 20 gauss. This limited range makes them best suited for measuring the residual magnetic field after demagnetization.

a. Hall-Effect (Gauss/Tesla) Meter: A Hall-Effect meter is an electronic device that provides a digital readout of the magnetic field strength in gauss or tesla units. The meters use a very small conductor or semiconductor element at the tip of the probe. Electric current is passed through the conductor. In a magnetic field, a force is exerted on the moving electrons which tend to push them to one side of the conductor.

A buildup of charge at the sides of the conductors will balance this magnetic influence, producing a measurable voltage between the two sides of the conductor. The presence of this measurable transverse voltage is called the Hall-Effect after **Edwin H. Hall**, who discovered it in 1879.





b. Probes: Are available with either tangential (transverse) or axial sensing elements. Probes can be purchased in a wide variety of sizes and configurations and with different measurement ranges. The probe is placed in the magnetic field such that the magnetic lines of force intersect the major dimensions of the sensing element at a right angle. Placement and orientation of the probe is very important and will be discussed in a later section. The voltage generated **Vh** can be related by the following equation.

$$Vh = I \; B \; Rh / b$$

Where:

Vh = Voltage generated;
I = Applied direct current;
B = Component of the magnetic field that is at a right angle to the direct current in the Hall element;
Rh = Hall Coefficient of the Hall element;
b = Thickness of the Hall element.

c. Portable MT Equipment: To properly inspect for cracks and other defects, it is important to become familiar with the different types of magnetic fields and the equipment used to generate them. One of the primary requirements for detecting a defect in a ferromagnetic material is that the magnetic field induced in the part must **intercept the defect at a 45 to 90 degree angle**. Flaws that are normal (90 degrees) to the magnetic field will produce the strongest indications because they disrupt more of the magnet flux.

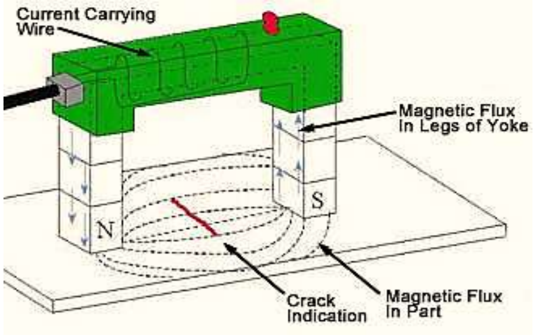
Proper inspection of a component is important to establish a magnetic field in at least two directions. One way to classify equipment **is based on its portability**. Some equipment is designed to be portable so that inspections **can be made in the field** and some is designed to be stationary for ease of inspection in the laboratory or manufacturing facility.

d. Permanent Magnets: Permanent magnets are sometimes used for magnetic particle inspection as the source of magnetism. The two primary types of permanent magnets are **bar magnets and horseshoe** (yoke) magnets. These industrial magnets are usually very strong and may require significant strength to remove them from a piece of metal. Some permanent magnets require over 50 pounds of force to remove them from the surface.

Because it is **difficult to remove** the magnets from the component being inspected, and sometimes difficult and dangerous to place the magnets, their **use is not particularly popular**. However, permanent magnets are sometimes used by divers for inspection in underwater environments or other areas, such as explosive environments, where electromagnets cannot be used. Permanent magnets can also be made small enough to fit into tight areas where electromagnets might not fit.

e. Electromagnets: Today, most of the equipment used to create the magnetic field used in MPI is based on electromagnetism. That is, using an electrical current to produce the magnetic field. An **electromagnetic yoke** is a very common piece of equipment that is used to establish a magnetic field. It is basically made by **wrapping an electrical coil** around a piece of soft ferromagnetic steel. A switch is included in the electrical circuit so that the current and, therefore, the magnetic field can be turned on and off.

They can be **powered with alternating current** from a wall socket or by direct current from a battery pack. This type of magnet generates a very strong magnetic field in a local area where the poles of the magnet touch the part being inspected. Some yokes can lift weights in excess of 40 pounds.



Portable yoke with a battery pack

Portable magnetic particle kit

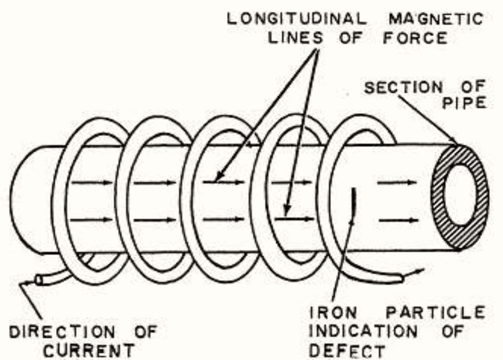
f. Prods: Prods are **handheld electrodes** that are pressed against the surface of the component being inspected to make contact for passing electrical current through the metal. The current passing between the prods creates a circular magnetic field around the prods that can be used in magnetic particle inspection. Prods are typically **made from copper** and have an insulated handle to help protect the operator. One of the prods has a trigger switch so that the current can be quickly and easily turned on and off. Sometimes there are **two prods** that are connected by any insulator (as shown in the image below) to facilitate one hand operation.

This is referred to as **dual prod** and is commonly used for weld inspections. If proper contact is not maintained between the prods and the component surface, an **electrical arcing can occur and cause damage** to the component. For this reason, the use of two prods is **not allowed** when inspecting **aerospace and other critical** components. To help prevent arcing, the prod tips should be inspected frequently to ensure that they are not oxidized, covered with scale, contaminants, or damaged.

Portable Prod Unit

The following applet shows two prods used to create a current through a conducting part. The resultant magnetic field roughly depicts the patterns expected from an magnetic particle inspection of an unflawed surface. The user is encouraged to manipulate the prods to orient the magnetic field to "cut across" suspected defects.

g. Portable Coils and Conductive Cables: Coils and conductive cables are used to establish a longitudinal magnetic field within a component. When a preformed **coil is used**, the component is placed **against the inside surface on the coil**. Coils typically have three or five turns of a copper cable within the molded frame. A foot switch is often used to energize the coil. Conductive cables are wrapped around the component. The cable used is typically extra flexible or extra flexible.



The number of wraps is determined by the magnetizing force needed and of course, the length of the cable. Normally, the wraps are kept as close together as possible. When using a coil or cable wrapped into a coil, amperage is usually expressed in ampere-turns. Ampere-turns is the amperage shown on the amp meter times the number of turns in the coil.

h. Stationary MT Equipment: Stationary magnetic particle inspection equipment is designed for **use in laboratory or production environment**. The most common stationary system is the wet horizontal (bench) unit. Wet horizontal units are designed to allow for batch inspections of a variety of components. The units have **head and tail stocks (similar to a lathe)** with electrical contact that the part can be clamped between. A circular magnetic field is produced with direct magnetization.

The tail stock can be moved and locked into place to accommodate parts of various lengths. To assist the operator in clamping the parts, the contact on the headstock can be moved pneumatically via a foot switch. Most units also have a **movable coil** that can be moved into place so the indirect magnetization can be used to produce a longitudinal magnetic field. Most coils have five turns and can be obtained in a variety of sizes. The wet magnetic particle solution is collected and held in a tank. A pump and hose system is used to apply the particle solution to the components being inspected.

Either the visible or fluorescent particles can be used. Some of the systems offer a variety of options in electrical current used for magnetizing the component. The operator has the option to use AC, half wave DC, or full wave DC. In some units, a demagnetization feature is built in, which uses the coil and decaying AC. To inspect a part using a head-shot, the part is **clamped between two electrical contact pads**. The magnetic solution, **called a bath**, is then flowed over the surface of the part.

The **bath** is then interrupted and a magnetizing current is applied to the part for a short duration, typically **0.5 to 1.5 seconds**. (Precautions should be taken to prevent burning or overheating of the part.) A circular field flowing around the circumference of the part is created. Leakage fields from defects then attract the particles to form indications. When the coil is used to establish a longitudinal magnetic field within the part, the part is placed on the inside surface of the coil. Just as done with a head shot, the bath is then flowed over the surface of the part.

A **magnetizing current** is applied to the part for a short duration, typically **0.5 to 1.5 seconds**, just after coverage with the bath is interrupted. (Precautions should be taken to prevent burning or overheating of the part.) Leakage fields from defects attract the particles to form visible indications. The wet horizontal unit can also be used to establish a circular magnetic field using a central conductor. This type of a setup is used to inspect parts that have an open center, such as gears, tubes, and other ring-shaped objects.

A central conductor is an electrically conductive bar that is usually made of copper or aluminum. The bar is inserted through the opening and the bar is then clamped between the contact pads. When current is passed through the central conductor, a **circular magnetic field flows** around the bar and enters into the part or parts being inspected.

Portable Coil

Conductive Cable

i. Portable Power Supplies: Portable power supplies are used to provide the necessary electricity to the prods, coils or cables. Power supplies are commercially available in a variety of sizes. **Small power** supplies generally provide up to **1,500A** of half-wave direct current or **alternating current** when used with a 4.5 meter cable. They are small and light enough to be carried and operate on either **120V or 240V** electrical service. When more power is necessary, **mobile power** supplies can be used.

Note: These units come with wheels so that they can be rolled where needed. These units also operate on 120V or 240V electrical service and can provide up to **6,000A** of AC or half-wave DC when 9 meters or less of cable is used.

13. Lights for MT Inspection:

Magnetic particle inspection can be performed using particles that are highly visible under white light conditions or particles that are highly visible under ultraviolet light conditions. When an inspection is being performed using the visible color contrast particles, no special lighting is required as long as the area of inspection is well lit. A light intensity of at least **1000 lux** (100 fc) is recommended when visible particles are used, but a variety of light sources can be used.

When fluorescent particles are used, special ultraviolet light must be used. Fluorescence is defined as the property of emitting radiation as a result of and during exposure to radiation. Particles used in fluorescent magnetic particle inspections are coated with a material that produces light in the visible spectrum when exposed to near-ultraviolet light.

This "**particle glow**" provides high contrast indications on the component anywhere particles collect. Particles that fluoresce yellow-green are most common because this color matches the peak sensitivity of the human eye under dark conditions. However, particles that turn red, blue, yellow, and green colors are available.

a. Ultraviolet Light: Ultraviolet light or "**black light**" is light in the 1,000 to 4,000 Angstroms (100 to 400nm) wavelength range in the electromagnetic spectrum. It is a very energetic form of light that is invisible to the human eye. Wavelengths above 4,000A fall into the visible light spectrum and are seen as the color violet. UV is separated according to wavelength into three classes: A, B, and C. The shorter the wavelength, the more energy that is carried in the light and the more dangerous it is to the human cells.

b. Basic Ultraviolet Lights: **UV bulbs** come in a variety of shapes and sizes. The more common types are the **low pressure tube**, high pressure spot, and the high pressure flood types. The tubular black light is similar in construction to the tubular fluorescent lights used for office or home illumination. These lights use a low pressure mercury vapor arc. Tube lengths of 6 to 48 inches are common.

Low pressure bulbs are most often used to provide general illumination to large areas rather than for illumination of components to be inspected. These bulbs generate a relatively large amount of white light, which is concerning since inspection specifications require less than two foot-candles of white light at the inspection surface.

c. Flood Lights: Are also used to illuminate the inspection area, since they provide even illumination over a large area. Intensity levels for flood lamps are relatively low because the energy is spread over a large area. They generally do not generate the required UV light intensity at the given distance that specifications require.

d. Spot Lights: Provide concentrated energy that can be directed to the area of inspection. A spot light will generate a six inch diameter circle of high intensity light when held fifteen inches from the inspection surface. One hundred watt mercury vapor lights are most commonly used, but higher wattages are available.

e. High Intensity Ultraviolet Lights: Metal halide bulbs 400 watts or "**super lights**" can be found in some facilities. This super bright light will provide adequate lighting over an area of up to ten times that covered by the 100 watt bulb. Due to their high intensity, excessive light reflecting from the surface of a component is a concern. Moving the light a greater distance from the inspection area will generally reduce this glare. Another type of high intensity light available is the micro-discharge light.

Obs.: This particular lights produce up to ten times the amount of UV conventional lights and readings up to 60,000 mW/cm^2, at 15 inches can be achieved.

14. Common Magnetic Field Indicators:

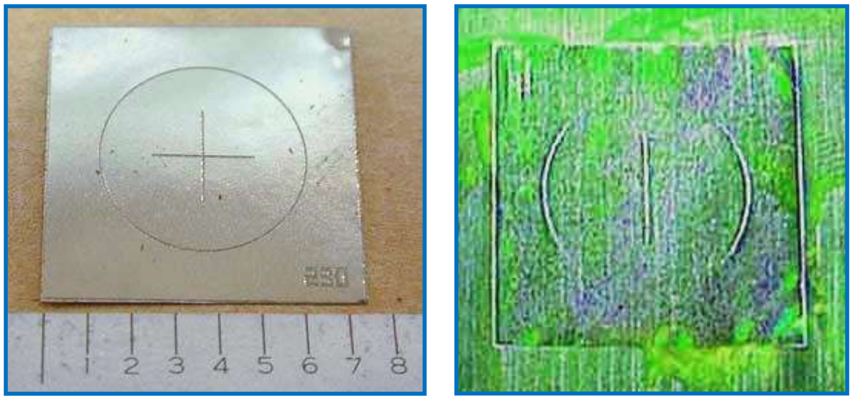
Determining whether a magnetic field is of adequate strength and in the proper direction is critical when performing magnetic particle testing. Knowing the direction of the field is important because the field should be as close to perpendicular to the defect as possible and no more than 45 degrees from normal. Being able to evaluate the field direction and strength is especially important when inspecting with a multi-directional machine, because when the fields are not balanced properly, a vector field will be produced that may not detect some defects.

There is actually no easy-to-apply method that permits an exact measurement of field intensity at a given point within a material. In order to measure the field strength, it is necessary to intercept the flux lines. This is impossible without cutting into the material and cutting the material would immediately change the field within the part. However, cutting a small slot or hole into the material and measuring the leakage field that crosses the air gap with a Gauss meter is probably the best way to get an estimate of the actual field strength within a part. Nevertheless, there are a number of tools and methods available that are used to determine the presence and direction of the field surrounding a component.

a. Gauss Meter or Hall Effect Gage: A Gauss meter with a Hall Effect probe is commonly used to measure the tangential field strength on the surface of the part. The Hall Effect is the transverse electric field created in a conductor when placed in a magnetic field. **Gauss meters, also called Tesla meters**, are used to measure the strength of a field tangential to the surface of the magnetized test object. The meters measure the intensity of the field in the air adjacent to the component when a magnetic field is applied.

The advantages of Hall Effect devices are: they provide a quantitative measure of the strength of magnetizing force tangential to the surface of a test piece, they can be used for measurement of residual magnetic fields, and they can be used repetitively. Their main disadvantages are that they must be periodically calibrated and they cannot be used to establish the balance of fields in multidirectional applications.

b. Quantitative Quality Indicators (QQI´s): Quantitative Quality Indicators (QQI´s) or Artificial Flaw Standard is often the preferred method of assuring proper field direction and adequate field strength. The QQI is a **thin strip** of either 0.002 or 0.004 inch thick **AISI 1005 steel**. A photo etch process is used to inscribe a specific pattern, such as concentric circles or a plus sign. QQIs are nominally 3/4 inch square, but miniature shims are also available.



The use of a QQI is also the only practical way of ensuring balanced field intensity and direction in multiple-direction magnetization equipment. QQIs are often used in conjunction with a Gauss meter to establish the inspection procedure for a particular component. They are used with the wet method only, and like other flux sharing devices, can only be used with continuous magnetization.

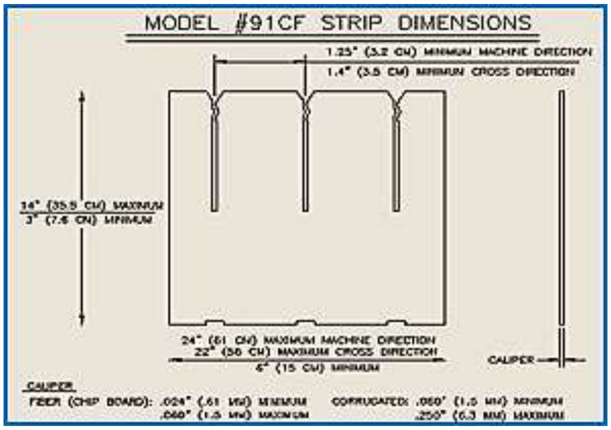
QQIs must be in intimate contact with the part being evaluated. This is accomplished by placing the shim on a part etched side down, and taping or gluing it to the surface. The component is then magnetized and particles applied. When the field strength is adequate, the particles will adhere over the engraved pattern and provide information about the field direction. When a multidirectional technique is used, a balance of the fields is noted when all areas of the QQI produce indications.

Some of the advantages of QQIs are: they can be quantified and related to other parameters, they can accommodate virtually any configuration with suitable selection, and they can be reused with careful application and removal practices. Some of the disadvantages are: the application process is somewhat slow, the parts must be clean and dry, shims cannot be used as a residual magnetism indicator as they are a flux sharing device, they can be easily damaged with improper handling, and they will corrode if not cleaned and properly stored.

c. Pie Gage: The **pie gage is a disk** of highly permeable material divided into **four, six, or eight sections** by non-ferromagnetic material. The divisions serve as artificial defects that radiate out in different directions from the center. The diameter of the **gage is 3/4 to 1 inch**. The divisions between the low carbon steel pie sections are to be no greater than 1/32 inch. The sections are furnace brazed and copper plated. The gage is placed on the test piece copper side up and the test piece is magnetized. After particles are applied and the excess removed, the indications provide the inspector the orientation of the magnetic field.

The principal application is on flat surfaces such as weldments or steel castings where dry powder is used with a yoke or prods. The **pie gage is not recommended** for precision parts with complex shapes, for wet-method applications, or for proving field magnitude. The gage should be demagnetized between readings. Several of the main advantages of the pie gage are that it is easy to use and it can be used indefinitely without deterioration. The pie gage has several disadvantages, which include: it retains some residual magnetism so indications will prevail after removal of the source of magnetization, it can only be used in relatively flat areas, and it cannot be reliably used for determination of balanced fields in multidirectional magnetization.

d. Slotted Strips: Slotted strips, also known as Burmah-Castrol Strips, are pieces of highly permeable ferromagnetic material with slots of different widths. They are placed on the test object as it is inspected. The indications produced on the strips give the inspector a general idea of the field strength in a particular area.



Advantages of these strips are: they are relatively easily applied to the component, they can be used successfully with either the wet or dry method when using the continuous magnetization, they are repeatable as long as orientation to the magnetic field is maintained, and they can be used repetitively. Some of the disadvantages are that they cannot be bent to complex configuration and they are not suitable for multidirectional field applications since they indicate defects in only one direction.

15. Dry and Wet Magnetic Particles:

The particles that are used for magnetic particle inspection are a key ingredient as they form the indications that alert the inspector to defects. Particles start out as tiny milled (a machining process) pieces of iron or iron oxide. A pigment (somewhat like paint) is bonded to their surfaces to give the particles color.

The metal used for the particles has high magnetic permeability and low retentivity. High magnetic permeability is important because it makes the particles attract easily to small magnetic leakage fields from discontinuities, such as flaws. Low retentivity is important because the particles themselves never become strongly magnetized so they do not stick to each other or the surface of the part. Particles are available in a dry mix or a wet solution.

a. Dry Magnetic Particles: Dry magnetic particles can typically be purchased in red, black, gray, yellow and several other colors so that a high level of contrast between the particles and the part being inspected can be achieved. The size of the magnetic particles is also very important. Dry magnetic particle products are produced to include a range of particle sizes. The fine particles are around **50 µm** (0.002 inch) in size, and are about three times smaller in diameter and more than 20 times lighter than the coarse particles (150 µm or 0.006 inch). This makes them more sensitive to the leakage fields from very small discontinuities. However, dry testing particles cannot be made exclusively of the fine particles.

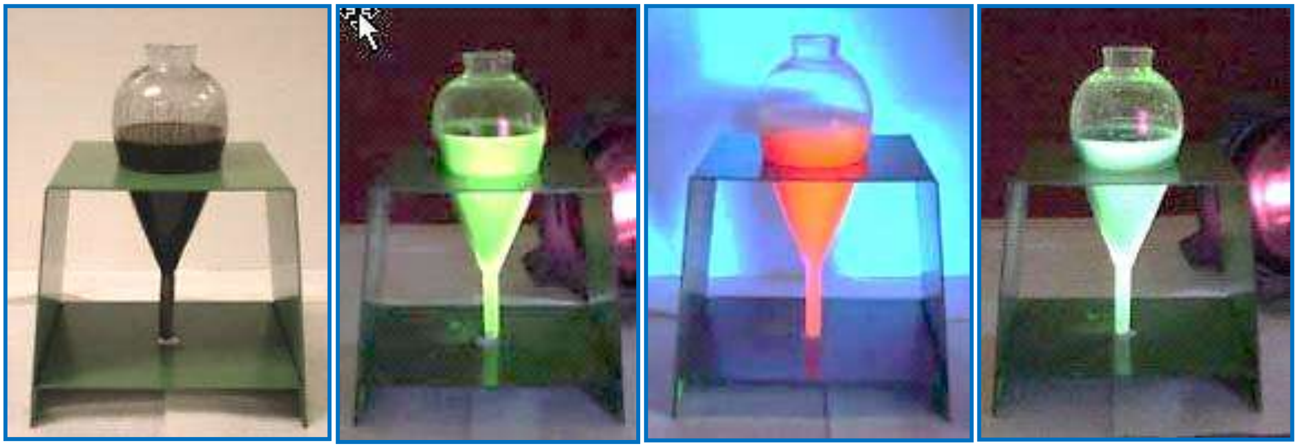
Coarser particles are needed to bridge large discontinuities and to reduce the powder's dusty nature. Additionally, small particles easily adhere to surface contamination, such as remnant dirt or moisture, and get trapped in surface roughness features. It should also be recognized that finer particles will be more easily blown away by the wind; therefore, windy conditions can reduce the sensitivity of an inspection.

Also, reclaiming the dry particles is not recommended because the small particles are less likely to be recaptured and the "once used" mix will result in less sensitive inspections. The particle shape is also important. Long, slender particles tend align themselves along the lines of magnetic force. However, research has shown that if dry powder consists only of long, slender particles, the application process would be less than desirable.

Obs.: Elongated particles come from the dispenser in clumps and lack the ability to flow freely and form the desired "cloud" of particles floating on the component. Therefore, added globular particles are shorter. The mix of globular and elongated particles results in a dry powder that flows well and maintains good sensitivity. Most dry particle mixes have particles with L/D ratios between one and two.

b. Wet Magnetic Particles: Magnetic particles are also supplied in a wet suspension such as water or oil. The wet magnetic particle testing method is generally more sensitive than the dry because the suspension provides the particles with more mobility and makes it possible for smaller particles to be used since dust and adherence to surface contamination is reduced or eliminated. The wet method also makes it easy to apply the particles uniformly to a relatively large area.

Wet magnetic particles products differ from **dry powder** products in a number of ways. One way is that both visible and fluorescent particles are available. Most non-fluorescent particles are **ferromagnetic iron oxides**, which are either **black or brown** in color. Fluorescent particles are coated with pigments that fluoresce when **exposed** to ultraviolet light. Particles that fluoresce **green-yellow** are most common to take advantage of the peak color sensitivity of the eye but other fluorescent colors are also available.



The particles used with the **wet method are smaller in size** than those used in the dry method for the reasons mentioned above. The particles are typically **10 µm** (0.0004 inch) and smaller and the synthetic iron oxides have particle diameters around **0.1 µm** (0.000004 inch). This very small size is a result of the process used to form the particles and is not particularly desirable, as the particles are almost too fine to settle out of suspension.

However, due to their slight residual magnetism, the **oxide particles** are present mostly agglomerated that settle out of suspension much **faster** than the individual particles. This makes it possible to see and measure the concentration of the particles for process control purposes. Wet particles are also a mix of long slender and globular particles.

The carrier solutions can be water or oil-based. Water-based carriers form quicker indications, are generally less expensive, present little or no fire hazard, give off no petrochemical fumes, and are easier to clean from the part. Water-based solutions are usually formulated with a corrosion inhibitor to offer some corrosion protection. However, oil-based carrier solutions offer superior corrosion and hydrogen embrittlement protection to those materials that are prone to attack by these mechanisms.

c. Suspension Liquids: Suspension liquids used in the **wet magnetic particle** inspection method can be either a well **refined light petroleum** distillate or **water containing additives**. Petroleum-based liquids are the most desirable carriers because they provided good wetting of the surface of metallic parts. However, water-based carriers are used more because of low cost, low fire hazard, and the ability to form indications quicker than solvent-based carriers.

- **Water-based carriers**: Must contain **wetting agents to disrupt surface films** of oil that may exist on the part and to aid in the dispersion of magnetic particles in the carrier. The wetting agents create foaming as the solution is moved about, so anti-foaming agents must be added. Also, since water promotes corrosion in ferrous materials, corrosion inhibitors are usually added.

- **Petroleum based carriers**: Require less maintenance because they evaporate at a slower rate than the water-based carriers. Therefore, petroleum based carriers might be a better choice for a system that gets only occasional use or when regularly adjusting the carrier volume is undesirable. Modern solvent carriers are specifically designed with properties that have flash points above 200°F and keep nocuous vapors low. Petroleum carriers are required to meet certain specifications such as AMS 2641.

16. Dry Particle Inspection:

In this magnetic particle testing technique, dry particles are **dusted onto the surface of the test object** as the item is magnetized. Dry particle inspection is well suited for the inspections conducted on rough surfaces. When an electromagnetic yoke is used, the AC or half wave DC current creates a **pulsating magnetic field that provides mobility to the powder**. The primary applications for dry powders are un-ground welds and rough as-cast surfaces.

Obs.: Dry particle inspection is also used to detect shallow subsurface cracks. Dry particles with half wave DC is the best approach when inspecting for lack of root penetration in welds of thin materials. Half wave DC with prods and dry particles is commonly used when inspecting large castings for hot tears and cracks.

Steps in performing an inspection using dry particles:

1. Prepare the part surface: The surface must be free of grease, oil or other moisture that could keep particles from moving freely. A thin layer of paint, rust or scale can **reduce test** sensitivity but can sometimes be left in place with adequate results. Specifications often allow up to **0.003 inch** (0.076 mm) of a nonconductive coating (such as paint) and **0.001 inch** max (0.025 mm) of a ferromagnetic coating (such as nickel) to be left on the surface. Any loose dirt, paint, rust or scale must be removed.

2. Apply the magnetizing force: Use permanent magnets, an electromagnetic yoke, prods, a coil or other means to establish the necessary magnetic flux.

3. Dust on the dry magnetic particles: Dust on a light layer of magnetic particles.

4. Blow off the excess powder: With the magnetizing force still applied, remove the excess powder from the surface with a few gentle puffs of dry air. The force of the air needs to be strong enough to remove the excess particles but not strong enough to dislodge particles held by a magnetic flux leakage field**.**

5. Terminate the magnetizing force: If the magnetic flux is being generated with an electromagnet or an electromagnetic field, the magnetizing force should be terminated. If permanent magnets are being used, they can be left in place.

6. Inspect for indications: Look for areas where the magnetic particles are clustered.

17. Wet Suspension Inspection:

Wet suspension magnetic particle inspection, more commonly known as **wet magnetic particle inspection**, involves applying the particles while they are suspended in a liquid carrier. Wet magnetic particle inspection is most commonly performed **using a stationary, wet, horizontal inspection unit,** but suspensions are also available in **spray cans** for use with an electromagnetic yoke. A wet inspection has several advantages over a dry inspection.

First, all of the surfaces of the component can be quickly and easily covered with a relatively uniform layer of particles. Second, the liquid carrier provides mobility to the particles for an extended period of time, which allows enough particles to float to small leakage fields to form a visible indication. Therefore, wet inspection is considered best for detecting very small discontinuities on smooth surfaces. On rough surfaces, however, the particles (which are much smaller in wet suspensions) can settle in the surface valleys and lose mobility, rendering them less effective than dry powders under these conditions.

Steps in performing an inspection using wet suspensions:

1. Prepare the part surface: The surface must be free of grease, oil and other moisture that could prevent the suspension from wetting the surface and preventing the particles from moving freely. A thin layer of paint, rust or scale will reduce test sensitivity, but can sometimes be left in place with adequate results. Specifications often allow up to **0.003 inch** (0.076 mm) of a nonconductive coating (such as paint) and **0.001 inch** max (0.025 mm) of a ferromagnetic coating (such as nickel) to be left on the surface. Any loose dirt, paint, rust or scale must be removed.

2. Apply the suspension: The suspension is sprayed or flowed over the surface of the part. Usually, the stream of suspension is diverted from the part just before the magnetizing field is applied.

3. Apply the magnetizing force: The magnetizing force should be applied immediately after applying the suspension of magnetic particles. When using a wet horizontal inspection unit, the current is applied in two or three short busts (1/2 second) which helps to improve particle mobility.

4. Inspect for indications: Look for areas where the magnetic particles are clustered. Surface discontinuities will produce a sharp indication. The indications from subsurface flaws will be less defined and lose definition as depth increases.

18. Inspection with Magnetic Rubber:

The **magnetic rubber technique** was developed for detecting **very fine cracks** and is capable of revealing finer cracks **than other magnetic techniques**. Additionally, the technique can be used to examine difficult to reach areas, such as **the threads** on the inside diameter of holes, where the molded plugs can be removed and examined under ideal conditions and magnification if desired. Of course, the inspection times are much longer.

The techniques use a **liquid (uncured) rubber containing suspended magnetic particles**. The rubber compound is applied to the area to be inspected on a magnetized component. Inspections can be performed using either an applied magnetic field, which is maintained while the rubber sets (active field), or the residual field from magnetization of the component prior to pouring the compound. A dam of modeling clay is often used to contain the compound in the region of interest. The magnetic particles migrate to the leakage field caused by a discontinuity. As the rubber cures, discontinuity indications remain in place on the rubber.

The rubber is allowed to completely set, which takes from 10 to 30 minutes. The rubber cast is removed from the part. The rubber conforms to the surface contours and provides a reverse replica of the surface. The rubber cast is examined for evidence of discontinuities, which appear as dark lines on the surface of the molding. The molding can be retained as a permanent record of the inspection.

Obs.: Magnetic rubber methods **require similar magnetizing systems** used for dry method magnetic particle tests. The system may include yokes, prods, clamps, coils or central conductors. Alternating, direct current, or permanent magnets may be used to draw the particles to the leakage fields. The direct current yoke is the most common magnetization source for magnetic rubber inspection.

19. Magnetization Techniques:

a. Continuous magnetization: Describes the technique where the magnetizing force is applied and maintained while the magnetic particles are dusted or flowed onto the surface of the component. In a wet horizontal testing unit, the application of the particles is stopped just before the magnetizing force is applied; but, since particles are still flowing over and covering the surface, this is considered continuous magnetization. In magnetic particle inspection, the magnetic particles can either be applied to the component while the magnetizing force is applied, or after it has been stopped.

b. Residual magnetization: Describes the technique where the magnetizing force is applied to magnetize the component and then stopped before applying the magnetic particles. Only the residual field of the magnetized component is used to attract magnetic particles and produce an indication. The continuous technique is generally chosen when maximum sensitivity is required because it has two distinct advantages over the residual technique. First, the magnetic flux will be highest when current is flowing and, therefore, leakage fields will also be strongest.

Field strength in a component depends primarily on two variables: the applied magnetic field strength and the permeability of the test object. Viewing the upper right portion of the **hysteresis loop above**, it is evident that the magnetic flux will be the strongest when the magnetizing force is applied. If the magnetizing force is strong enough, the flux density will reach the point of saturation. When the magnetizing force is removed, the flux density will drop to the retentivity point.

The two gray traces show the paths the flux density would follow if the magnetizing force was applied and removed at levels below that required to reach saturation. It can be seen that the flux density is always highest while the magnetizing current is applied. This is independent of the permeability of a material. However, the **permeability** of the material is very important. High permeability materials do not retain a strong magnetic field so flux leakage fields will be extremely weak or nonexistent when the magnetizing force is removed. Therefore, materials with **high magnetic permeability are not suited** for inspection using the residual technique.

c. Field Direction and Intensity: When determined the direction of the field, it is important to notice the defect must produce a significant disturbance in the magnetic field to produce an indication. It is difficult to detect discontinuities that intersect the magnetic field at an angle less than 45^o. When the orientation of a defect is not well established, components should be magnetized in a minimum of two directions at approximately right angles to each other.

Depending on the geometry of the component, this may require longitudinal magnetization in two or more directions, multiple longitudinal and circular magnetization or circular magnetization in multiple directions. Determining strength and direction of the fields is especially critical when inspecting with a multidirectional machine. If the fields are not balanced, a vector field will be produced that may not detect some defects.

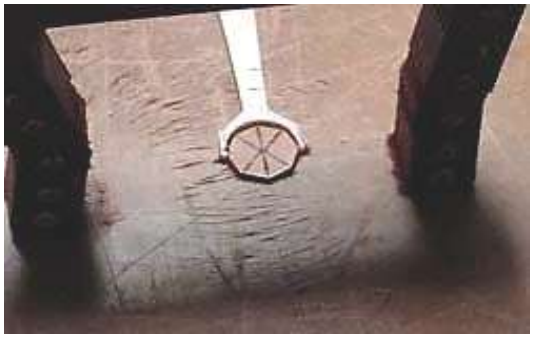
Depending on the application, pie gages, QQI's, or a gauss meter can be used to check the field direction. The pie gage is generally only used with dry powder inspections. QQI shims can be used in a variety of applications but are the only method recommended for use in establishing balanced fields when using multidirectional equipment.

d. Field Strength: The applied magnetic field must have sufficient strength to produce a satisfactory indication, but not so strong that it produces non-relevant indications or limits particle mobility. If the magnetizing current is excessively high when performing a wet fluorescent particle inspection, particles can be attracted to the surface of the part and not be allowed to migrate to the flux leakage fields of defects.

When performing a dry particle inspection, an excessive longitudinal magnetic field will cause furring. Furring is when magnetic particles build up at the magnetic poles of a part. When the field strength is excessive, the magnetic field is forced out of the part before reaching the end of the component and the poles along its length attract particles and cause high background levels. Adequate field strength may be determined by:

- Performing an inspection on a standard specimen that is similar to the test component and has known or artificial defects of the same type, size, and location as those expected in the test component. QQI shims can sometimes be used as the artificial defects.
- Using a gauss meter with a Hall Effect probe to measure the peak values of the tangent field at the surface of the part in the region of interest. Most specifications call for a field strength of 30 to 60 gauss at the surface when the magnetizing force is applied.
- Looking for light furring at the ends of pipes or bars when performing dry particle inspections on these and other uncomplicated shapes.

Formulas for calculating current levels should only be used to estimate current requirements. The magnetic field strength resulting from calculations should be assessed for adequacy using one of the two method discussed above. Likewise, published current level information should also be used only as a guide unless the values have been established for the specific component and target defects of the inspection at hand.



e. Using a Pie Gage: A pie gage is placed copper side up and held in contact with the component as the magnetic field and particles are applied. Indications of the leakage fields provide a visual representation of defect direction within the component.

Pie gages work well on flat surfaces, but if the surface is concave or convex, inaccurate readings may occur. The pie gage is a flux sharing device and requires good contact to provide accurate readings.

f. Quantitative Quality Indicator (QQI) Shims: Quantitative Quality Indicator (QQI) flaw shims are used to establish proper field direction and to ensure adequate field strength during technique development. The QQI's are also flux sharing devices and must be properly attach so as not to allow particles to become trapped under the artificial flaw. Application using **super glue** is the preferred way of attaching the artificial flaw, but does not allow for reuse of the shims. Shims can also be attached with tape applied to just the edge of the shim. It is recommended that the tape be impervious to oil, not be fluorescent, and be 1/4 to 1/2 inch in width.

One example would be the center area of a yoke or Y shaped component. Oftentimes, the flux density will be near zero in this area. If two legs of a Y are in contact with the pad in circular magnetization, it must be determined if current is flowing evenly through each leg. A QQI on each leg would be appropriate under such conditions. QQI's can be used to establish system threshold values for a defect of a given size. By attaching a QQI shim with three circles (40%, 30% and 20% of shim thickness) to the component, threshold values for a specific area of the component, can be established.

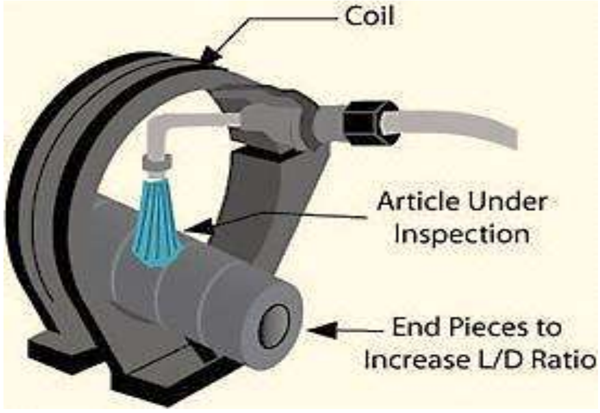
Begin by applying current at low amperage and slowly increasing it until the largest flaw is obtained. The flux density should be verified and recorded using a Hall effects probe. The current is then increased until the second circle is identified and the flux density is again recorded. As the current is further increased, the third ring is identified and the current values are recorded.

g. Gauss Meter Inspection: There are several types of Hall effects probes that can be used to measure the magnetic field strength. Transverse probes are the type most commonly used to evaluate the field strength in magnetic particle testing. Transverse probes have the Hall Effect element mounted in a thin, flat stem and they are used to make measurements between two magnetic poles. Axial probes have the sensing element mounted such that the magnetic flux in the direction of the long axis of the probe is measured.

To make a measurement with a transverse probe, the probe is positioned such that the flat surface of the Hall Effect element is transverse to the magnetic lines of flux. The Hall Effect voltage is a function of the angle at which the magnetic lines of flux pass through the sensing element.

The greatest Hall Effect voltage occurs when the lines of flux pass perpendicularly through the sensing element. If not perpendicular, the output voltage is related to the cosine of the difference between 90 degrees and the actual angle. The peak field strength should be measured when the magnetizing force is applied. The field strength should be measured in all areas of the component to be inspected.

h. Length to Diameter Ratio: When establishing a longitudinal magnetic field in component using a coil or cable wrap, the ratio of its length (in the direction of the desired field) to its diameter or thickness must be taken into consideration. If the length dimension is not significantly larger than the diameter or thickness dimension, it is virtually impossible to establish a field strength strong enough to produce an indication. An L/D ratio of at least two is usually required.



The formula for determining the necessary current levels presented in the appendix of ASTM 1444 are only useful if the L/D ratio is greater than two and less than 15. Don't forget that the formula only provides an estimate of the necessary current strength and this strength must be confirmed in other ways.

The preferred method is to examine parts having known or artificial discontinuities of similar type and size in the location of the targeted flaws; or by using quantitative quality indicator (notched) shims. A second method is to use gauss Metter with a tangential field Hall Effect probe to measure the field strength, which must be in the range of 30 to 60 G.

i. Use of End Pieces: If the component does not meet the minimum **L/D ratio** requirement, end pieces may be used to essentially lengthen the component. The end pieces must be the same diameter or thickness of the component under test and must made of ferromagnetic material. Sometime it is possible to stack multiple parts end to end to increase the L/D ratio. The parts must butt fairly tightly together as shown in the image. The urge to inspect the entire length of butted parts at one time must be resisted. This urge is especially strong when using a central conductor with wet-horizontal equipment to inspect components such as nuts.

To increase the efficiency of the inspection, a number of nuts are often placed on a central conductor and a circular magnetic field is established in the parts all at once. This is perfectly acceptable when inspecting the components with a circular magnetic field. However, when switching to a longitudinal field, it is very tempting to simply slide the coil out so that it is centered on the stack of nuts, which are left in place on the central conductor. This is unacceptable technique for a couple of reasons.

First, remember that the effective field extends a distance on either side of the coil center approximately equal to the radius of the coil. Parts outside of the effective distance will not receive adequate magnetization. The parts will need to be repositioned in the coil in order to examine the entire length of the stack. An overlap area of about ten percent of the effective magnetic field is required by most specifications. Additionally, if the central conductor is left clamped in the stocks, the parts will be at the center of the coil where the field strength is the weakest. The parts should be placed at the inside edge of the coil for best results.

20. Particle Concentration:

The concentration of particles in the **suspension** is a very important parameter in the inspection process and must be closely controlled. The **particle concentration** is checked after the suspension is prepared and regularly monitored as part of the quality system checks. ASTM E-1444-01 requires concentration checks to be performed every eight hours or at ever shift change. The standard process used to perform the check requires agitating the carrier for a minimum of thirty minutes to ensure even particle distribution.

A **sample** is then taken in a pear-shaped **100 ml** centrifuge tube having a stem graduated to **1.0 ml in 0.05 ml** increments for fluorescent particles, and graduated to **1.5 ml in 0.1 ml** increments for visible particles. The sample is then demagnetized so that the particles do not clump together while settling. The sample must then remain undisturbed for a minimum of **60 minutes** for a petroleum-based carrier or 30 minutes for a water-based carrier, unless shorter times have been documented to produce results similar to the longer settling times. The volume of settled particles is then read.

Acceptable ranges are **0.1 to 0.4 ml** for fluorescent particles and **1.2 to 2.4 ml** for visible particles. If the particle concentration is out of the acceptable range, particles or the carrier must be added to bring the solution back in compliance with the requirement. Particle loss is often attributed to "drag out." Drag out occurs because the solvent easily runs off c components and is recaptured in the holding tank. Particles, on the other hand, tend to adhere to components, or be trapped in geometric features of the component. These particles will be "drug out" or lost to the system and will eventually need to be replaced.

a. Particle Condition: After the particles have settled, should be examined for brightness and agglomeration. Fluorescent particles should be evaluated under ultraviolet light and visible particles under white light. Brightness of the particles should be evaluated weekly by comparing the particles in the test solution to those in an unused reference solution that was saved when the solution was first prepared. The brightness of the two solutions should be relatively the same. Additionally, the particles should appear loose and not lumped together. If the brightness or the agglomeration of the particles is noticeably different from the reference solution, the bath should be replaced.

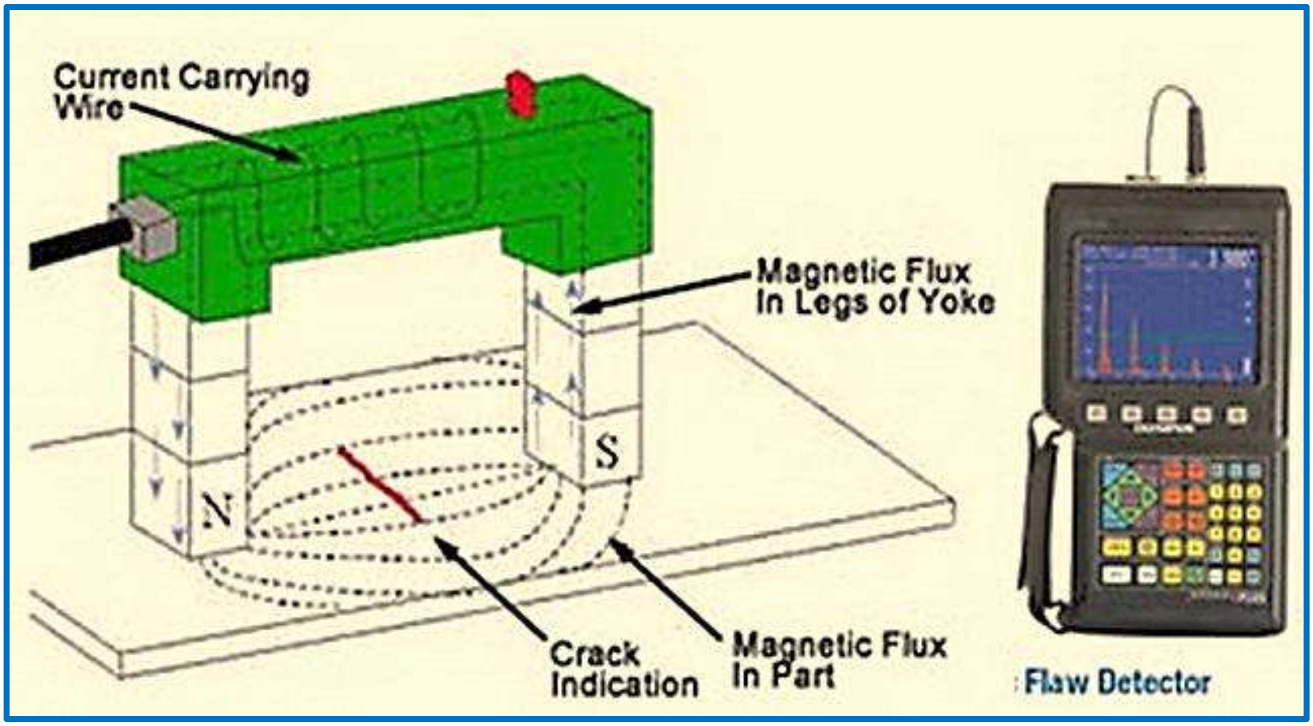
b. Suspension Contamination: The suspension solution should also be examined for evidence of contamination. Contamination primarily comes from inspected components. Oils, greases, sand, and dirt will be introduced to the system through components. If the area is unusually dusty, the system will pick up dust or other contaminates from the environment. This examination is performed on the carrier and particles collected for concentration testing.

The graduated portion of the tube is viewed under ultraviolet and white light when fluorescent particles are being used and under white light when visible particles are being used. The magnetic particles should be examined for foreign particles, such as dirt, paint chips and other solids. Differences in color, layering or banding within the settled particles would indicate contamination. Some contamination is to be expected but if the foreign matter exceeds 30 percent of the settled solids, the solution should be replaced.

The liquid carrier portion of the solution should also be inspected for contamination. Oil in a water bath and water in a solvent bath are the primary concerns. If the solution fluoresces brightly when fluorescent particles are being used, this can be an indication that dye is being dislodged from the particles by the mixing pump.

While not technically contamination, this condition should be further evaluated by allowing the collected sample bath to set for 10 to 12 hours and viewed under ultraviolet light. If a band that fluoresces brighter than the bulk of particles is evident on top of the settled solids, the bath contains excessive unattached fluorescent pigments and should be discarded.

c. Water Break Test: A daily water break check is required to evaluate the surface wetting performance of water-based carriers. The water break check simply involves flooding a clean surface similar to those being inspected and observing the surface film. If a continuous film forms over the entire surface, sufficient wetting agent is present. If the film of suspension breaks (water break) exposing the surface of the component, insufficient wetting agent is present and the solution should be adjusted or replaced.



21. Practical Examples:

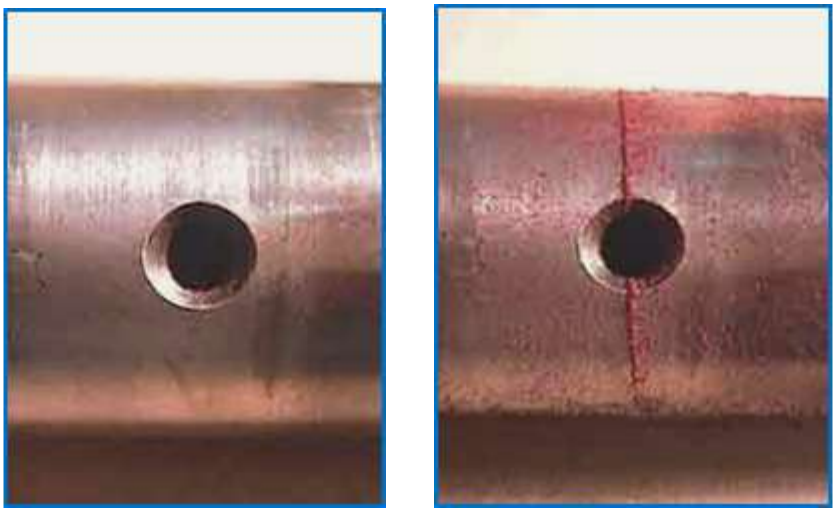
One of the advantages that a magnetic particle inspection has over some of the other nondestructive evaluation methods is that flaw indications generally resemble the actual flaw. This is not the case with NDT methods, such as **Ultrasonic** and **Eddy Current** inspection, where an electronic signal must be interpreted. When magnetic particle inspection is used, cracks on the surface of the part appear as sharp lines that follow the path of the crack. Flaws that exist below the surface of the part are less defined and more difficult to detect. Below are some examples of magnetic particle indications produced using dry particles.

Field Magnetic Particle Inspections

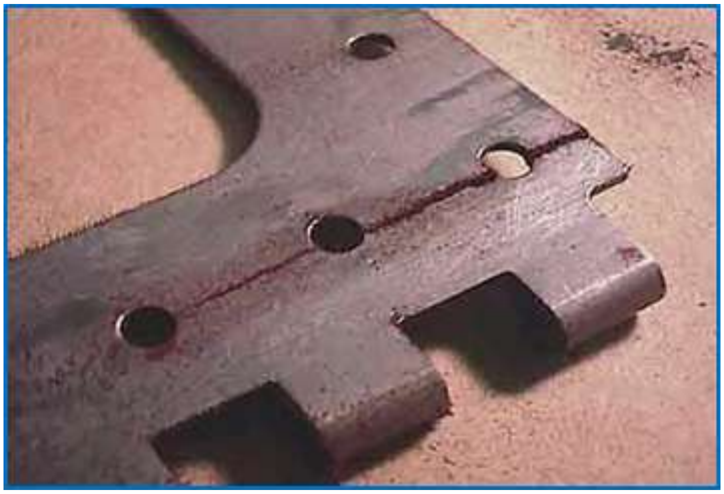
Indication of a crack in a saw blade

Indication of cracks in a weldment

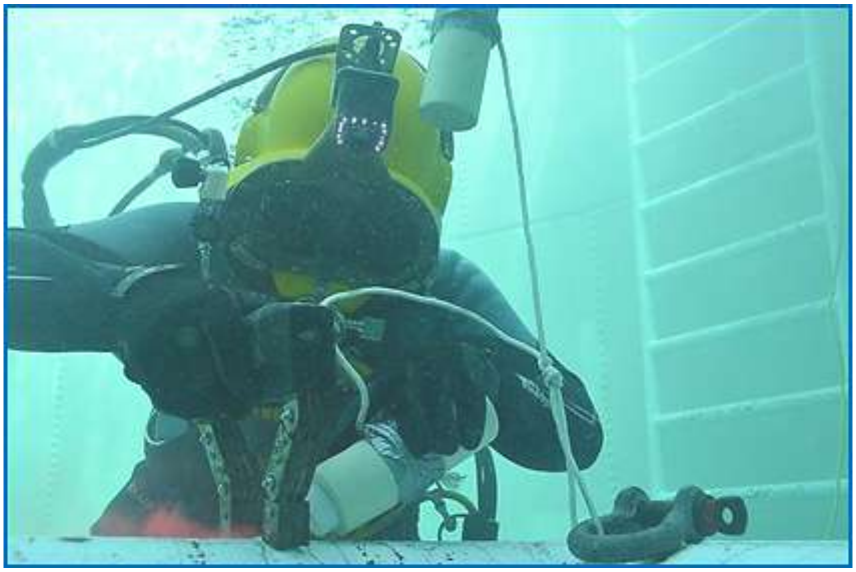
Indication of cracks originating at a fastener hole



Before and after inspection pictures of cracks emanating from a hole



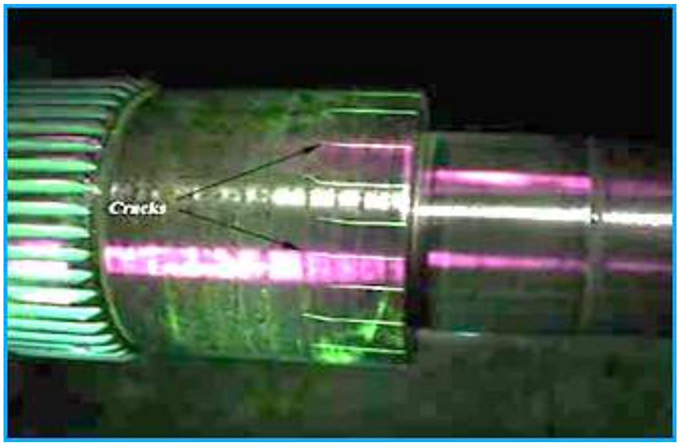
Indication of cracks running between attachment holes in a hinge



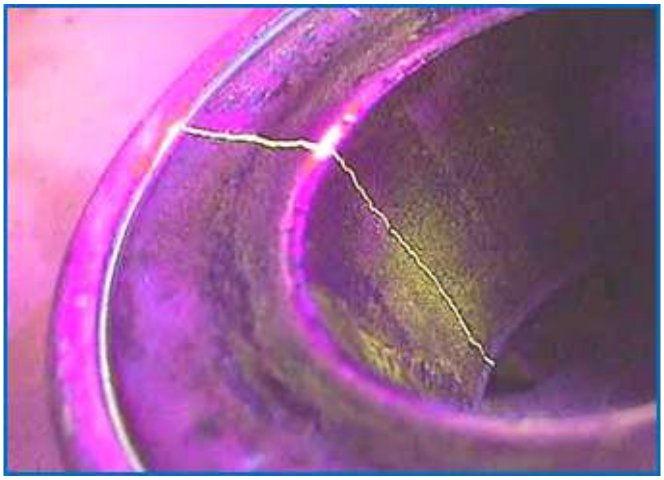
Underwater MT Inspection

22. Examples of Fluorescent Wet Magnetic Particles Indications:

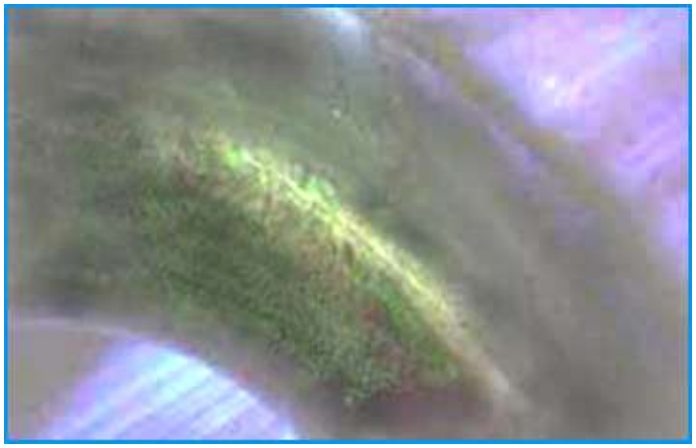
The indications produced using the wet magnetic particles are sharper than dry particle indications formed on similar defects. When fluorescent particles are used, the visibility of the indications is greatly improved because the eye is drawn to the "glowing" regions in the dark setting. Below are a few examples of fluorescent wet magnetic particle indications.



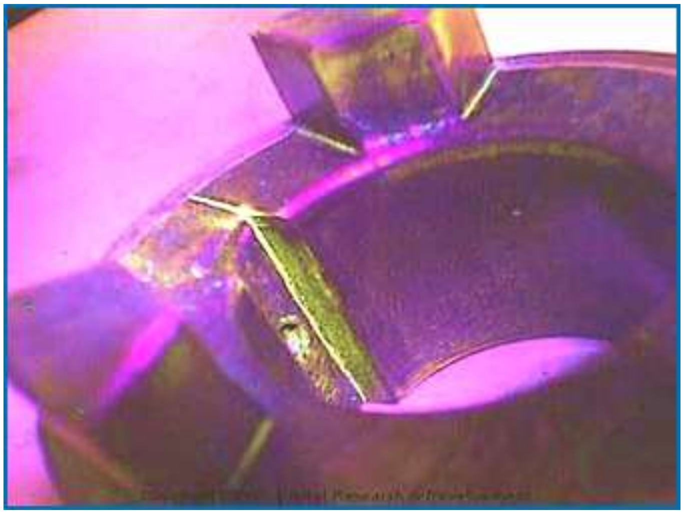
Magnetic particle wet fluorescent indication of cracks in a drive shaft.



Magnetic particle wet fluorescent indication of a crack in a bearing.



Magnetic particle wet fluorescent indication of a crack in a crane hook.



Magnetic particle wet fluorescent indication of a crack at a sharp radius.

Magnetic particle wet fluorescent indication of a crack in a casting

Magnetic particle wet fluorescent indication of cracks at a fastener hole.

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