A SunCam online continuing education course

Nondestructive Examination

by

Roger Cantrell

Learning Objectives

This course introduces the student to the basic concepts of six Nondestructive Examination (NDE) methods used in construction and periodic inspection of metallic products, e.g. building frames, bridges, piping systems, boilers, etc. The physical principle of each method is described. Advantages and disadvantages of each method are discussed and some examples of application are provided. Many applications involve NDE of welds and the student is referred to the SunCam companion course Welding Technology for further study. Upon completion of this course, the student should be able to:

- Understand the physical principles of six fundamental NDE methods
- Understand the advantages and disadvantages of each method
- Appreciate some of the considerations for applying each method

NONDESTRUCTIVE EXAMINATION

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1.0 Introduction

Nondestructive examination (NDE) is examination of an object in a manner which will not impair its future usefulness or serviceability. Most NDE is for identifying physical imperfections but some methods, e.g. ECT are also used for other purposes. Items naturally contain imperfections which result from construction processes (casting, rolling, welding, etc.) or result from service (corrosion, fatigue, etc.). Imperfections below a certain type, size, or number are acceptable if they do not prevent the item from serving its intended function. While some NDE is performed for "information only", e.g. as part of a failure analysis, most NDE is performed for product acceptance.

Guidance (and legal constraints) on what type, size, and number of imperfections are acceptable and what NDE methods are to be used can be found in regulatory documents, contract documents, applicable Codes, design specifications, etc. Most NDE is implemented in accordance with a written program complying with construction standards such as the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code Section V, American Welding Society D1.1 (Structural Steel), or the American Society for Nondestructive Testing (ASNT) standard SNT-TC-1A.

An indication is a response to an NDE method. An indication could include penetrant bleed out, a shadow on a radiograph, etc. Indications are classified as relevant or non-relevant. Non-relevant indications are due to known configurations and are dismissed unless they could mask a relevant indication. For example, if a bushing on a shaft is PT examined, bleed out will occur at the interface between the bushing and shaft. Since this bleed out is due to a known and acceptable configuration, it is dismissed unless it could mask nearby relevant indications. If an indication cannot be explained by a known (and acceptable) condition, it is relevant. Relevant indications must be compared to pre-established acceptance criteria either directly or by comparison to a calibration standard. If the relevant indication exceeds the acceptance criteria, it is a flaw.

An NDE "method" is an examination process based on a physical principle to identify the existence and extent of imperfections. There are multitudes of variations within a given "method". Volumes can and have been written on these variations. This course covers only the basic physical principles of six commonly used NDE methods, visual (VT), liquid penetrant (PT), magnetic particle (MT), radiography (RT), ultrasonic (UT), and eddy current (ECT).

2.0 Visual Examination (VT)

In the most basic NDE method, an experienced examiner visually identifies surface imperfections which may not be obvious to the layman. The value of visual examination depends largely on the knowledge and experience of the examiner. Visual examination can ascertain imperfections such as scratches, wear, cracks, corrosion, erosion, misalignment or movement of parts, and leakage. Visual examination will show large imperfections and may also direct the examiner to smaller questionable areas that should be confirmed by another NDE method. In-process visual examination can detect and aid in eliminating imperfections that might become flaws in a completed product.

Formal qualification of the examiner may or may not be required. For most Codes, a knowledgeable craftsman (welder, fitter) may perform visual examination of all fabrication steps except final acceptance at which point a qualified visual examiner is usually required. Examination sensitivity can be improved by fiber optics, magnifying lenses, boroscopes, mirrors, etc. Visual examination determines the general condition of an object and may be performed independently or as part of other nondestructive examinations. For welds, using weld gauges and rules allow preparations, weld sizes, fit-up, and undercut to be measured. Comparison samples may be useful such as kits available from the American Welding Society (AWS) showing “good” and “bad” weld contours. The cost of visual examination is generally less than other NDE methods and can be applied to the widest range of materials.

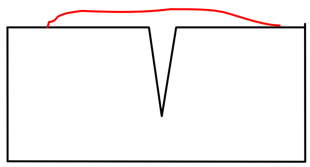
3.0 Liquid Penetrant Examination (PT)

An old mechanics trick, dating back to the Model T and before, was to soak a part (brake drum, cylinder head, etc.) in kerosene, wipe the part clean, and sprinkle it with powdered chalk. Residual kerosene held in imperfections by capillary action after wiping the part clean would wet the chalk. Modern PT uses the same principle but a colored (usually red) penetrant with low viscosity is used. The area of interest is coated with penetrant. Sufficient dwell time is allowed, typically thirty minutes, and then bulk penetrant is removed from the surface. Residual penetrant remains held in any surface-opening imperfections by capillary attraction. A developer is sprayed on the area which draws this residual penetrant from any imperfections identifying the imperfection by contrast. The principle is illustrated in Figure PT-1. Acceptance criteria are usually based on the size of the indication which, because of bleed out, is larger than the actual imperfection.

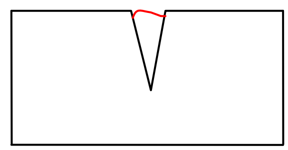
Once penetrant is applied, the surface must remain wet, which limits area of inspection at a given time.

Penetrant examination is sensitive for locating imperfections open to the surface in any non-porous material. Porous material will hold the penetrant in the pores which would then bleed out when the developer is applied masking relevant indications. PT is relatively inexpensive and easy to perform. Penetrant examination is the alternative on non-magnetic metals such as aluminum, magnesium, brass, copper, austenitic stainless steel, and titanium where MT is not possible.

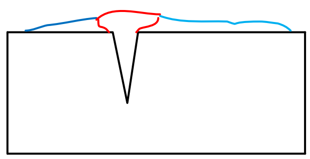
If contamination fills an imperfection, it may prevent the penetrant from entering masking their discovery. Additionally, mechanical “smearing” of surfaces may close imperfections sufficiently to mask their discovery. An example is weld metal peening which consists of striking the weld metal with various devices (pneumatic peening tool, shot peening, etc.) to work it during welding for distortion control. Smearing may also be caused by abusive grinding or machining.



1. Area flooded with penetrant



2. Bulk penetrant removed but residual penetrant remains in imperfection



3. Developer draws penetrant out which is visible by contrasting colors

Figure PT-1
Principle of Liquid Penetrant Examination

<u>4.0 Magnetic Particle Examination (MT)</u>

As early as 1868 cannon barrels were magnetized and a compass moved along the barrel. The compass needle would move at any imperfections. Certain (ferromagnetic) materials may be magnetized by aligning magnetic domains on an atomic or molecular level. Magnetization can be induced by a permanent magnet or (for MT examination) by the magnetic field surrounding an electric current (electromagnet). A magnetic field can be modeled as lines of force (flux) which form complete loops and never cross. This flux preferentially flows through any nearby imperfection free ferromagnetic material uninterrupted. At any surface or near-surface imperfection the flux lines leak out of the ferromagnetic material where it will collect iron powder. The particles may be wet or dry, may be florescent or non-florescent, and are usually colored for contrast. This principle is illustrated in Figure MT-1.

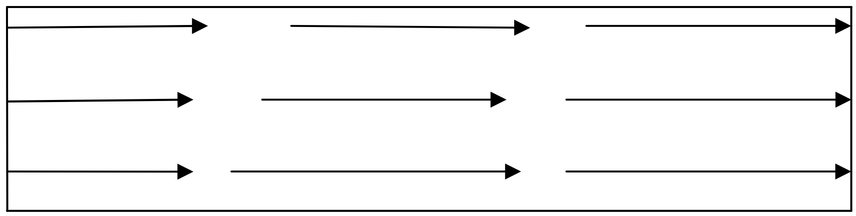


Figure MT-1A
This figure illustrates the portion of the magnetic field within the part. The closed magnetic loop is completed outside the part (not shown). With no imperfections this portion of the field remains entirely within the part.

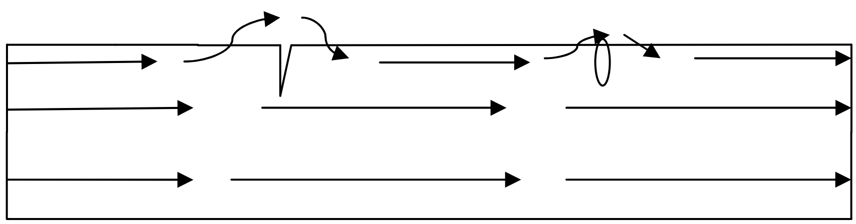


Figure MT-1B
This figure illustrates the portion of the magnetic field within the part. The closed magnetic loop is completed outside the part (not shown). At surface or near-surface imperfections some of the field leaks out where it is detected by iron powder.

Imperfections that lie transverse to the flux will be most readily detected. If the imperfection is parallel to the flux, the flux will pass on either side of the imperfection and not create the leakage necessary for detection. Detection of imperfections oriented between these extremes will vary in proportion. For similar reasons, MT examination is not sensitive to porosity. An MT examination is usually done twice with the flux oriented 90 degrees apart. MT reveals imperfections filled with carbon, slag or other non-magnetic foreign material that would not be found using the liquid penetrant method. The magnetic flux is not affected by these contaminating materials which could obstruct penetrant examination. MT examination reveals imperfections open to the surface and, as opposed to PT, slightly below the surface.

The flux can be induced by a permanent magnet or, for MT examination, by utilizing the flux surrounding an electric current at right angles to the current ("right hand rule" from basic physics). There are two basic methods of portable magnetization, i.e. yoke or prod. With the yoke method, an electromagnet (yoke) is used to magnetize the part being examined. No current flows through the part. With the prod method, two contact electrodes (prods) are used to produce a local current within the part between the prods magnetizing the area by the flux encircling the current. With the prod method, care must be taken to avoid arc strikes on the part being examined.

MT cannot be performed on nonmagnetic materials such as aluminum, magnesium, austenitic stainless steel, nickel, copper, or brass.MT examination may permanently magnetize a part. If this is harmful to subsequent processing such as welding, demagnetization may be required. Magnetization could create arc blow in subsequent welding.

<u>5.0 Radiographic Examination (RT)</u>
Radiography employs x-rays or gamma emitting isotopes (e.g. Cobalt-60) to detect both surface and subsurface imperfections such as porosity, inclusions, and cracks. Similar to medical x-rays, a source of radiation is placed on one side of the item and recording film is placed on the other side. Areas of different density within the item will appear as shadows on the developed film (radiograph).A void will appear darker on the radiograph as it permits more radiation to pass through than the surrounding material. A denser area, such as a piece of tungsten broken off during GTAW welding, will show up brighter on the radiograph since the denser tungsten absorbs more radiation than the surrounding material. Personnel with extensive training and experience set up the "shot" and interpret ("read") the resulting radiograph. See Figure RT-1A.

Devices called penetrometers are placed between the item and the film (placed not to mask any indications). These devices are designed to produce indications of known size on the radiograph and hence prove the examination was set up properly, if one can see the penetrometer one should see any actual indications. Crack-like imperfections lined up with or parallel to the radiation beam will be detected most clearly since a significant portion of the radiation beam will pass through the imperfection. Similarly, rounded imperfections such as voids or shrinkage in castings show up well with RT. Crack-like imperfections which are transverse to the radiation beam will not show contrast on the radiograph since all portions of the radiation beam will have passed through essentially the same mass of material. This is opposite to UT examination (RT and UT complement each other).RT has also been used for purposes other than material soundness such as seating of a valve or for finding lost items within a pipe or vessel.

The radiograph becomes a record of the examination; however, it may deteriorate over time. Methods have been developed to digitize radiographs to avoid this problem. There is a severe health risk to radiation which necessitates shielding or evacuation of work areas during radiography. Stringent Federal and State regulations control the source. Surface irregularities such as valleys between weld beads, if not removed, could be mistaken for internal imperfections/flaws.

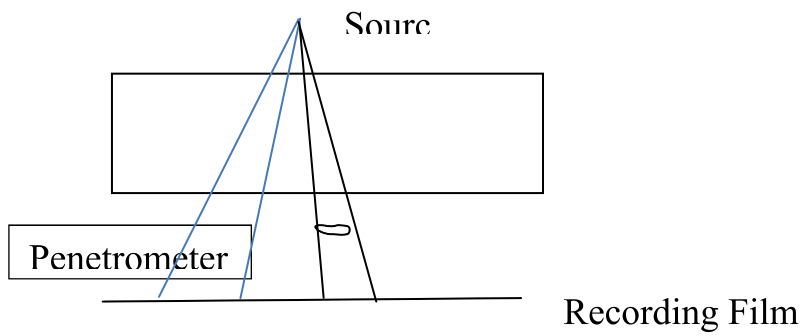


Figure RT-1A
Basic Single Wall Radiograph

Access to both sides of the part is usually required, one side for the radiation source and the other side for the film. Double walled radiographs, such as for a pipe weld, can be produced by offsetting the angle between the source and film such that the near and far sides of the pipe weld do not overlap on the film. See Figure RT-2A. However, distortion must be considered when interpreting such radiographs. An alternative is to use gamma holes. Gamma holes are openings in the pipe for inserting the source such that it is centrally located inside the pipe. Film is placed around the outside of the pipe. After RT, the hole is plugged with a designed method. See Figure RT-2B. The Pipe Fabrication Institute (PFI) publishes standardized generally accepted designs for gamma hole plugs.

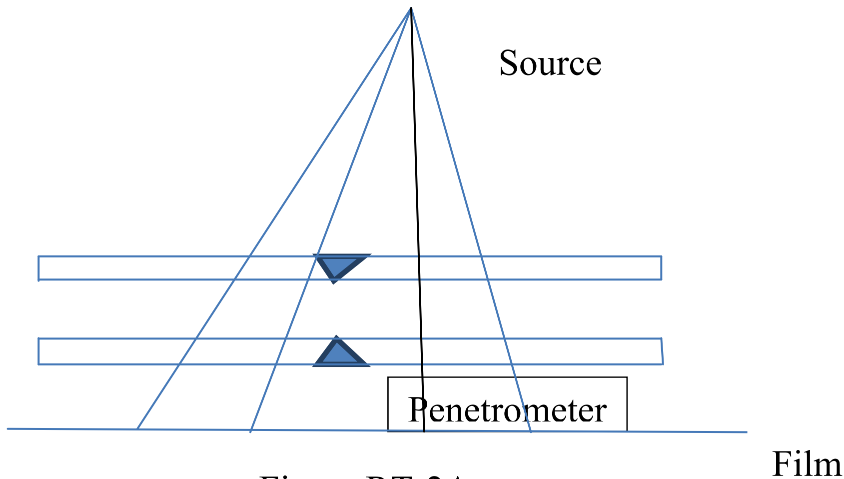


Figure RT-2A
Double Wall Radiograph. Near and far side of weld both appear on radiograph since source is offset so portions of weld do not overlap on film.

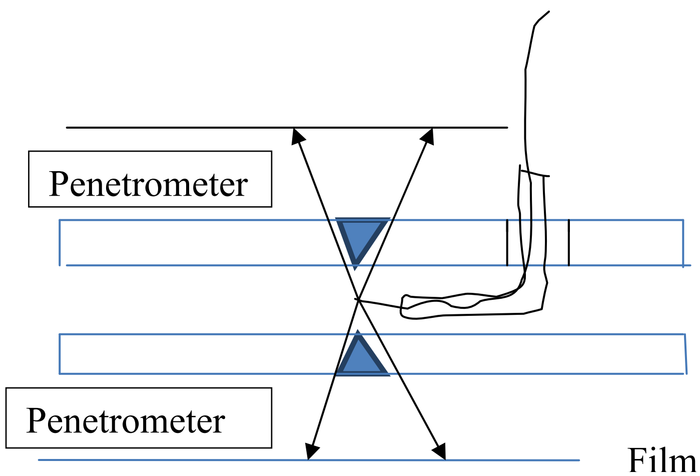


Figure RT-2B
Using a gamma hole, the source is guided to the center of the pipe through a guide tube. After exposure, the source and tube are withdrawn and the gamma hole plugged.

6.0 Ultrasonic Examination (UT)

Ultrasonic examination uses reflections from high frequency sound waves to detect imperfections and determine unknown thicknesses. Typically the waves are generated as pulses and reflections are captured by the same transducer between pulses. The concept is shown in Figure UT-1. The transducer is supported by electronics for generating the sound waves, collecting the reflections, and displaying the responses. The beam can be introduced at many angles, frequencies, amplitudes, etc. to optimize the results. As opposed to RT, only one side of the work needs to be accessible. Ultrasonic examination is also used for thickness measurements by correlating the time required for the wave to reflect from the back surface of an item with the time required for a standard of known thickness.

Ultrasonic examination best detects linear imperfections that are transverse to the sound beam in contrast to radiographic examination which best detects linear imperfections that are parallel to the radiation beam. This distinction becomes less significant for more rounded imperfections such as gross porosity or casting shrinkage voids. Imperfections that are parallel to the sound beam will not reflect a signal back to the transducer because the sound will continue on either side of the imperfection rather than reflecting from it as shown in Figure UT-1, Detail C. In Figure UT-1, Detail D, the sound waves are generated at an angle to the surface to optimize detection when there is some idea of the most likely orientation of imperfections. Such an example could be the fusion line of a weld. Knowledge of trigonometry is very useful to a UT examiner.

UT thickness readings are often used to locate metal of adequate thickness when determining the size of a weld patch or replacement spool piece in piping. The thickness readings determine the extent of unseen internal damage by erosion, corrosion, etc. such that the necessary size of the repair can be predetermined.

With mechanization, multiple frequencies, beam angles, etc. many UT systems are highly sophisticated. In the nuclear power industry, UT is used extensively to locate imperfections that have developed in service and to define (characterize) them such that flaw growth analysis and fracture mechanics can be used to predict suitability of a component for additional operating cycles.

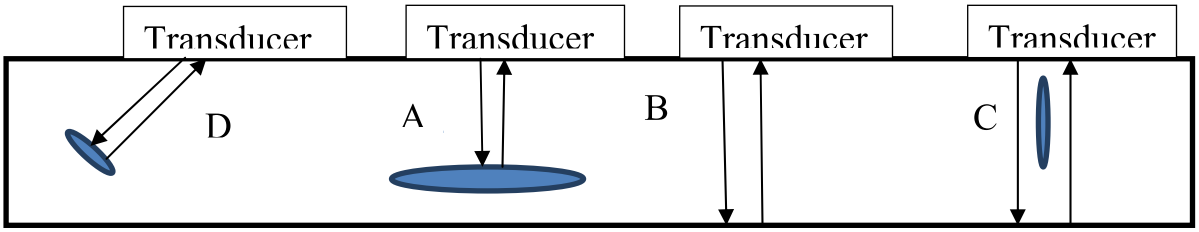


Figure UT-1
Detail A:Imperfection transverse to ultrasonic wave. Reflection provides optimum detection.
Detail B:Absence of an imperfection. Reflection is optimum for thickness measurements.
Detail C:Imperfection parallel to ultrasonic wave results in weak reflection.
Detail D: Randomly oriented imperfectiondetected with an angled sound beam.

Although a couplant is used between the transducer and part, surface roughness may still require mechanical prepping such as grinding, machining, sandblasting, etc. to ensure good contact. Coarse grain materials (e.g. nickel base alloys, austenitic stainless steel, and castings) and weld metals are more difficult to examine. The larger grain boundaries reflect sound unrelated to any imperfections confusing the detection of actual imperfections. Small or thin parts are difficult to inspect due to problems with near-field acoustics. Considerable experience is required to interpret results. Calibration standards, which are necessary for meaningful examinations, are not available for all base metal thicknesses and geometries.

7.0 Eddy Current Examination (ECT)

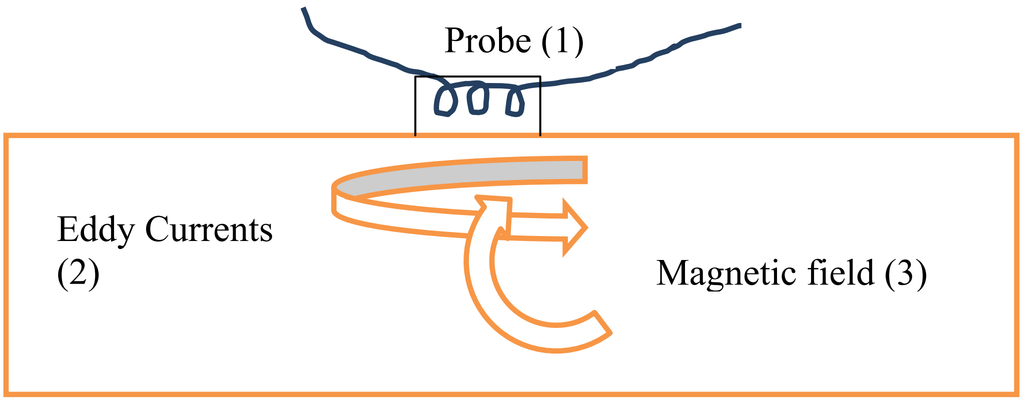
The first use of eddy currents as an NDE method was reported in 1879, almost twenty years before the discovery of x-rays. However, significant use of ECT did not begin until after World War II. ECT depends on measuring the impedance of a coil due to changes in the flow of eddy currents in a conducting item. An alternating current (AC) coil (probe) placed near a conducting material will induce an alternating magnetic field in the material. This field creates eddy currents in the material which in turn produce a magnetic field which opposes the probe field. This inductive coupling is similar to what occurs in a transformer core or a power line coupling with the earth. This opposing field can then be compared to calibration standards with known imperfections. See Figure ECT-1.

ECT is frequently used to find imperfections in heat exchanger tubing and similar long thin shapes. ECT can also be used to measure non-conducting coating thicknesses and to sort unknown materials using appropriate calibration standards.

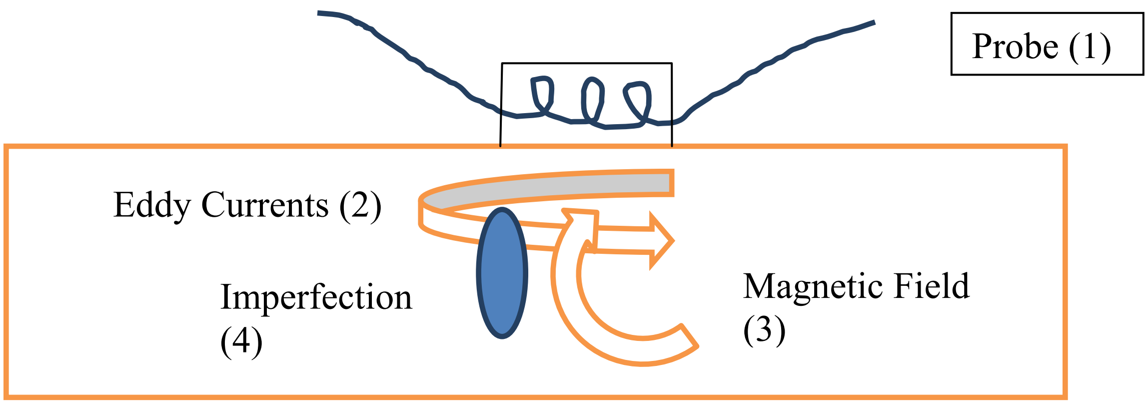
For a homogenous material, a certain response is received in the coil. An imperfection is a non-conducting region that will inhibit the eddy currents causing a change in response in the coil, i.e. an NDE indication. The imperfection is measured by comparing the unknown response to the response of a calibration standard of known imperfection size and orientation.

The distance of the probe from a conducting material affects the response. By determining the response at various distances from a conducting material, the thickness of a non-conducting coating can be determined by placing the probe against the coating. The non-conducting coating has no effect on the response other than displacing the probe from the conducting material.

Different materials have different conductivities which affect the eddy currents. By comparing the eddy current response of known materials against the response of unknown materials, materials can be sorted by general composition, e.g. carbon steel, low alloy steel, stainless steel, etc. By the same principle, material can be sorted for grain size, heat treatment condition, etc.



Alternating magnetic field from the probe (1) induces eddy currents (2) within the part. These eddy currents induce their own magnetic field (3) within the part creating measurable impedance in the probe (1)
Figure ECT-1A



An imperfection (4) alters the eddy currents (2) and magnetic field (3) changing the measurable impedance created in the probe (1). Changes in the measurable impedance would also be caused by distance of the probe from the material, material composition, grain size, heat treatment condition, etc.
Figure ECT-1B