

Non-destructive testing for product and facility safety

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To insure product safety and reliability in the field of manufacturing, non-destructive testing is often used to eliminate potential defects before shipping and to analyze defects when accidents have occurred. Professor Hirayama of Osaka Sangyo University has contributed this article on the relationship between non-destructive testing and product safety and reliability.

1. Introduction

Approximately four years have passed since the Product Liability Law went into effect here in Japan in July 1995. Since that time, manufacturers have redoubled their efforts to supply safe products and facilities to comply with this law.

These days, the importance of non-destructive evaluation techniques has been greatly increasing in all fields of manufacturing. This technology is used to prevent accidents and breakdown, to analyze such accidents and breakdowns when they do occur, and to improve safety and reliability.

The purposes for using non-destructive methods can be grouped into two major categories. One area of non-destructive testing focuses on improving manufacturing processes by detecting defects that occur during those processes. The other major area consists of evaluating the quality and reliability life of products and facilities by achieving a quantitative understanding of the relationship between product defects and product strength.

In general, the term non-destructive testing (NDT) is used to refer to such techniques as examining types, shapes, and dimensions and determining whether a product has any internal or external defects. Such techniques do not cause damage to or destruction of the products.

The term non-destructive inspection (NDI) is also frequently used, but this term refers to techniques to determine product acceptance/rejection by comparing the non-destructive test results with pre-determined criteria. For the production line to run smoothly from the initial stages of production up to product completion, defects occurring at each process must be detected using non-destructive testing, those defects must be eliminated at early stages of the process, and defective products must not be introduced to the next process. Also, the cause of defect occurrence must be investigated and feedback from the investigation must be given to the production process. In this way, production line problems can be quickly detected, and countermeasures can be taken to prevent product defects.

In addition, preventive maintenance based on maintenance inspections is crucial to maintaining the safe operation of equipment and production items during their use. Maintenance inspections can be broadly classified into inspections with equipment running and inspections requiring equipment stoppage. Non-destructive testing according to the purpose is required to be able to diagnose deterioration due to materials as well as due to the occurrence of all sorts of defects caused by usage environment factors.

Nowadays, non-destructive methods are not only used to detect defects, but also to consider the effects of those defects on the reliability of equipment and production items. Research is also under way on general evaluation methods for reliability life and safety factors in fracture mechanics. These evaluation methods are called non-destructive evaluation (NDE).

Fig.1 below shows a sample flowchart of non-destructive evaluation with general considerations for welded structures.¹⁾

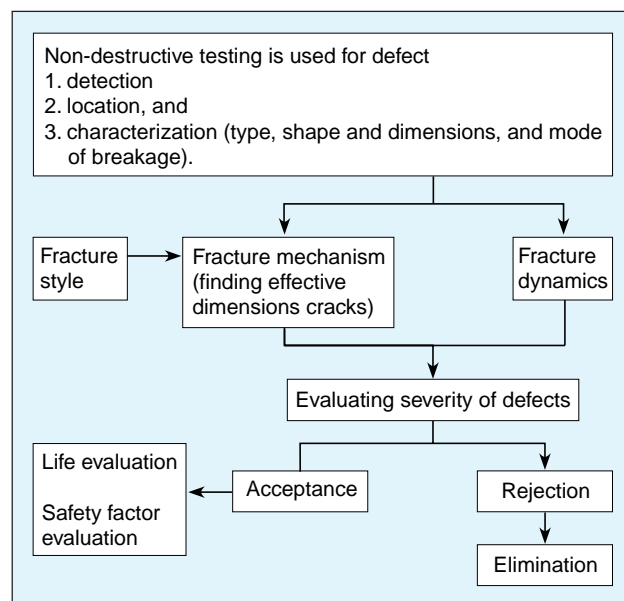


Fig. 1 Flowchart for non-destructive evaluation techniques

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First of all, non-destructive testing is used to detect defects inside the materials, then defects must be located and differentiated according to type, and then characterized according to such factors as shape and dimensions.

Next, the load and environmental conditions are considered in hypothesizing the fracture mechanism, and defect severity is determined according to fracture dynamic handling. Using those results, the final acceptance/rejection determination (the last defect screening) is made, and accepted items are once more evaluated for safety factor and life.

2. Types of non-destructive tests

Most non-destructive testing methods are based on principles using properties such as ultrasonic frequencies, electromagnetism, and radioactive emissions, in other words utilizing physical phenomena. For reference, Table 1 shows NASA classifications of non-destructive measurement techniques.²⁾

The types of non-destructive tests can be grouped according to the locus of the test, for example, whether the test obtains information related to the internal section or whether it obtains information related to the surface or the surface layer. The following examples show non-destructive tests belonging to each of these categories.

- (1) Non-destructive testing to obtain information related to the internal section
 - Radiographic testing and ultrasonic testing
- (2) Non-destructive testing to obtain information related to the surface or the surface layer
 - Visual testing, liquid penetrant testing, magnaflux testing, and electromagnetic induction (eddy current) testing

At this point, I would like to discuss some representative non-destructive measurement techniques that have been gaining acceptance for application to product and facility safety.

3. Radiographic testing

Radiographic testing is widely used as a non-destructive test method for detecting defects inside test items. In particular, this type of test is used for checking welded joints in steel structures such as ships, tubing, bridge girders, and pressure vessels. Objective test results can be obtained regarding the type and dimensions of the defects detected, and so this test method is widely used for quality assurance of products and facilities.

Radiographic testing utilizes the properties of x-rays, γ -rays, and neutron rays to permeate matter. In other words, if there is an aperture inside the test item, the rays permeating that section will differ in intensity from the rays permeating the surrounding wholesome section. Detectors (e.g., x-ray film and instruments for measuring radiation) are used to create images showing the differences in intensity of such radiation, and observing these images can reveal the existence of apertures.

Radiographic testing can be broadly divided into direct methods, fluoroscopy methods, and digital methods.

3-1 Direct methods

Direct methods are the most common type of radiographic testing. In these techniques, the varying density of radiation that penetrates the test object is projected (irradiated) directly onto x-ray film, then the resulting photographic image is visually inspected.

Table 1 NASA standard classifications of non-destructive measurement techniques

Classification	Test methods	Classification	Test methods
Mechanical-optical methods	<ul style="list-style-type: none"> • Visual-optical method • Holographic interference method • Photoelastic membrane method • Stress paints • Strain gauge • Micro hardness • Liquid penetrant method • Volatile liquid method • Filter particle method • Leakage detection 		<ul style="list-style-type: none"> • Electrical induction method • Natural electron emission method • Microwave emission
		Thermal methods	<ul style="list-style-type: none"> • Contact temperature measurement • Thermoelectromotive force method • Infrared radiometer method • Liquid crystal method • Electrothermal method
		Acoustic and ultrasonic methods	<ul style="list-style-type: none"> • Acoustic shock method • Acoustic vibration method • Eddy current noise vibration method • Acoustic emission method • Ultrasonic pulse reflection method • Ultrasonic permeation method • Ultrasonic surface wave method • Ultrasonic threshold angle method
Radioactive transmission methods	<ul style="list-style-type: none"> • Radiographic test method • γ-ray radiography • Neutron radiography • Transmitted radiation measurement method • Back-scattering x-ray method • Auto-radiography • Radioactive gas penetrant method • Positron extinction method 	Chemical and analytical methods	<ul style="list-style-type: none"> • Chemical spot test • Electrolytic probe method • Laser probe method • Ion scatter method • Ion probe method • Auger analysis method • Fluorescent x-ray method • Neutron emission spectroscopy • Charged particle emission method
Electromagnetic and electrical methods	<ul style="list-style-type: none"> • Magnetostatic field method • Magnetic particle method • Nuclear magnetic resonance method • Barkhausen effect • Eddy current method • Electrical resistance method • Charged particle method • Corona discharge method 		

The quality of direct radiographic images varies according to a number of factors such as the quality of the x-rays or γ -rays, focus dimensions, and the combination of photographic arrangement with the x-ray film used and the intensifying screen. In addition, to evaluate the image quality of radiographs, radiation meters consisting of wires of various diameters are photographed together, and the size of the minimum wire diameter discriminated is measured.

Different x-ray films have different levels of sensitivity, film contrast (gamma values) and graininess.

High-speed x-ray film can be used to photograph small amounts of exposure, but the film contrast and graininess are poor, resulting in poor images in which it is difficult to discern defects. On the other hand, low-speed x-ray film exhibits good film contrast and graininess, resulting in good images in which it is easier to discern defects. However, low-speed film requires more exposure.

Exposure can be reduced by placing the x-ray film between intensifying screens. Three types of intensifying screens are lead foil intensifying screens, metal fluorescent intensifying screens, and fluorescent intensifying screens. The most commonly used type is the lead foil intensifying screen, but the metal fluorescent and fluorescent intensifying screens are used with particularly low-intensity radiation.

To obtain high-quality images in radiographs, one must determine exposure conditions that will yield the proper density.

3-2 Fluoroscopy methods

Fluoroscopy methods commonly employ an image intensifier. The image is photographed at amplified luminosity using a high-resolution image pickup tube (TV camera), and then the x-ray image is displayed on a TV monitor, where it is observed. Fig. 2 shows the construction of an industrial x-ray TV device using an image intensifier.

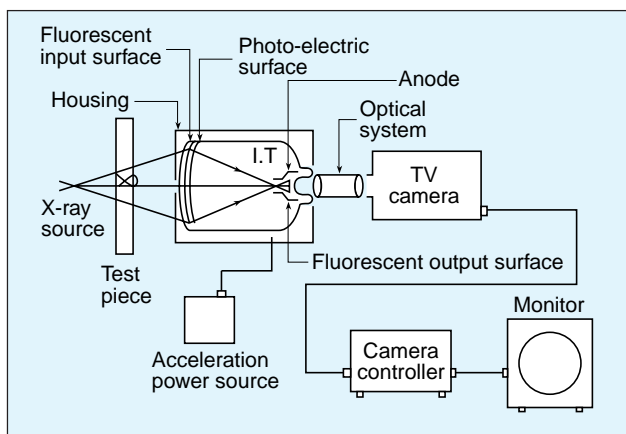


Fig. 2 Construction of an industrial X-ray TV device

The image intensifier in Fig.2 works as follows. The x-rays irradiate the fluorescent input surface, where the x-rays are converted into weak visible rays, and then at the photo-electric surface (which is in contact with the fluorescent input surface) the rays are emitted as photo-electrons. These photo-electrons are accelerated at the

acceleration power source and then concentrated by the static electric lens. At the fluorescent output surface, the rays are reduced and become visible images with markedly intensified luminosity. The luminosity intensification ratio reaches several thousand times as bright. When these rays pass through the optical system, they are photographed with the image pickup tube and displayed on the monitor. Some fluoroscopy methods use an x-ray vidicon instead of an image intensifier. The x-ray vidicon has a better signal-to-noise ratio than the image intensifier, but the radiographic field is rather small, making it difficult to use with large test pieces.

Whether defects can be seen with radiation photography depends on the relationship between the size of the ΔD of the contrast showing the defect image and the size of the ΔD_{min} of the discrimination limit contrast with which the naked eye can see the defect.

Fig. 3 shows the relationship between the defect image width W and the ΔD_{min} of the discrimination limit contrast. The discrimination limit contrast remains constant in the range with a large width for the defect image, but when the defect image width decreases beyond a certain size, the discrimination limit contrast becomes progressively greater.

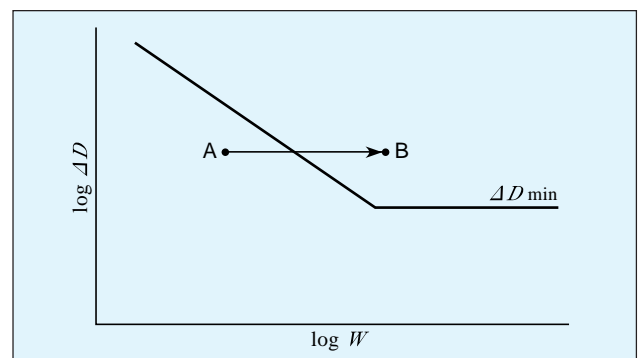


Fig. 3 Improving image quality

Point A in Fig. 3 shows the contrast for a certain width of a defect image. Because this point A is in a smaller range than the discrimination limit contrast, it cannot be discerned. In other words, this represents “an invisible defect”. If we enlarge the defect width at point A to the width at point B, this becomes “a visible defect” which can be discerned. One crucial condition at this time is that the contrast must not be reduced when enlarging the image. Achieving this condition requires x-ray equipment with minute focus, called micro-focus.

Attempting to detect defects smaller than a few dozen microns was difficult with conventional x-ray equipment, which had focus dimensions from 0.4 mm to 2.5 mm. To prevent blurring from the size of the focus in such cases, it was necessary to take the photograph with the test piece closer to the x-ray film, as shown in Fig. 4 (a). However, the ability to use this arrangement with small defects was limited by the defect dimensions unless the contrast could be increased, as Fig. 3 clearly shows.

Fig. 4 (b) shows an example of using micro-focus to detect minute defects. The test piece can be left at the same distance from the x-ray film and the defect can be enlarged without causing image blurring. This is called the enlarged radiographic method.

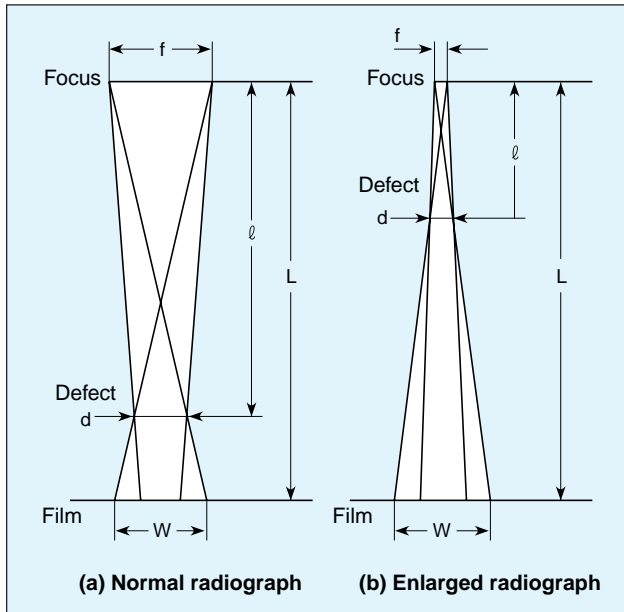


Fig. 4 Normal and enlarged radiographs

To this point, most of the radiographic tests discussed have been those using x-ray film, but some fluoroscopy methods use TV monitors instead of x-ray film. Furthermore, adding image enhancing equipment makes possible such enhancements as integral emphasis and contour emphasis. Using these with enlargement fluoroscopy makes it possible to improve image quality and resolution to the same level as x-ray film. Photos 1 and 2 show examples of such applications.

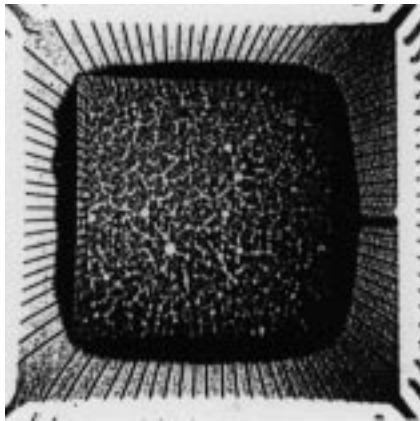


Photo 1 Enlarged radiograph of LSI (about 12×)



Photo 2 Enlarged radiograph of LSI (about 200×)

3-3 Digital method

The digital method uses semiconductors and NaI scintillation detectors for image data, and then reconstructs the images with a computer. Computer tomography (CT) is a typical example of this method. Having gained wide acceptance, CT is often used in medical applications and is also rapidly becoming common in industrial uses as well.

4. Neutron radiography

Thermal neutron rays have absorption coefficients for chemical elements that differ greatly from x-rays. In particular, neutron rays have difficulty penetrating light chemical elements such as hydrogen (H) and boron (B) and specific chemical elements such as cadmium (Cd), tin (Sn), and gadolinium (Gd). As a result, neutron rays can be used for radiography to obtain different information from conventional x-ray and γ -ray radiographs.

Such features of neutron rays can be used for composite materials consisting of a combination of light and heavy elements, for example, testing hydrides covered with materials such as steel or lead, or for testing the bonding condition of metals bonded together.

The following are some areas in which this technology is expected to be used.

- (a) Testing nuclear fuels for cracking, unevenness, and damage
- (b) Testing processed items, engine nozzles, and electrical parts of all types of rockets for space development, as well as their priming tubes and detonating fuses
- (c) Testing all types of aircraft turbine blades for clogging, testing for body corrosion, testing the adhesion condition of the honeycomb structure of the wings, and testing fuel supply tubing
- (d) Real time observation of conditions such as fuel supply conditions inside an engine, hydraulic oil inside hydraulic equipment, and hydraulic flow through tubing
- (e) Testing all types of new composite materials
- (f) Research in medicine and archaeology, such as checking excavated items

The source of neutron rays has conventionally been nuclear reactors and radioactive isotopes. More recently, the development of an easy-to-use small accelerator has led to the wide acceptance of non-destructive testing using neutron rays.

5. Defect detection methods using back-scattering x-rays

To apply x-ray radiographic testing, the test piece must be placed between the x-ray device and the detector (usually x-ray film). Fig. 5 shows the principle for using the defect detection method with back-scattering x-rays. A fine bundle of rays are used for x-ray irradiation without touching the test piece, and the intensity of the scattering x-rays generated to the rear (on the source side) of the test piece is measured. By scanning the test piece, this method can be used to detect defects in the surface layer on the x-ray source side of the test piece. Because the intensity of the scattering x-rays can be measured on the same side as the location of the x-ray source, this method has the special ability to detect defects from a single side, in the same manner as ultrasonic defect testing.

Another aspect of this method deserving attention is that strong back-scattering x-rays, i.e., high-contrast signals, can be obtained even for low-absorption materials with low atomic numbers. This method is suitable for materials with low atomic numbers that could not be detected with radiographic methods, and airport luggage inspections are one typical application for this method.

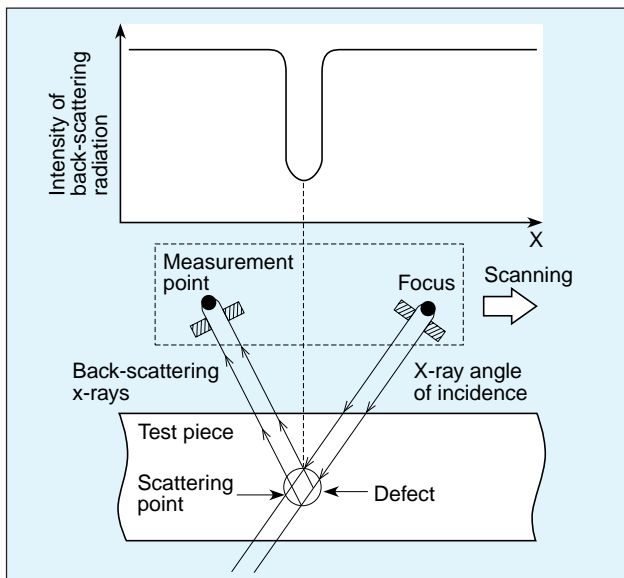


Fig. 5 Principle of back-scattering x-ray defect detection method

6. Infrared thermography

Infrared thermography relies on changes in temperature distribution at the surface of the test piece to detect defect-induced changes in thermal conduction characteristics. Lately, rapid strides have been made in temperature measurement technology using infrared ray transmission, and infrared thermography devices no longer are used merely for macro regions. Equipment has now been developed that is capable of measuring heat in micro regions as small as 10 μm in diameter. These developments are being used to evaluate thermal design of semiconductor components such as ICs and LSIs, as well as to determine acceptance/rejection for temperature distribution from minute joint areas.

7. Ultrasonic testing

The human ear is said to be capable of hearing frequencies in a normal range of 20 to 20,000 Hz (Hertz). Frequencies above the range that can be heard by the human ear are called ultrasonic frequencies. Ultrasonic frequencies can be propagated in materials such as metals just as if from a lighthouse. In other words, ultrasonic frequencies have excellent directional characteristics, and the sound waves travel on a direct path in a tight bundle. Ultrasonic waves traveling on a direct path have the characteristic of reflecting on boundary surfaces such as different objects or gaps. This characteristic can be used to detect defects inside objects, and measure the size and location. Fig. 6 shows the principle of ultrasonic testing.

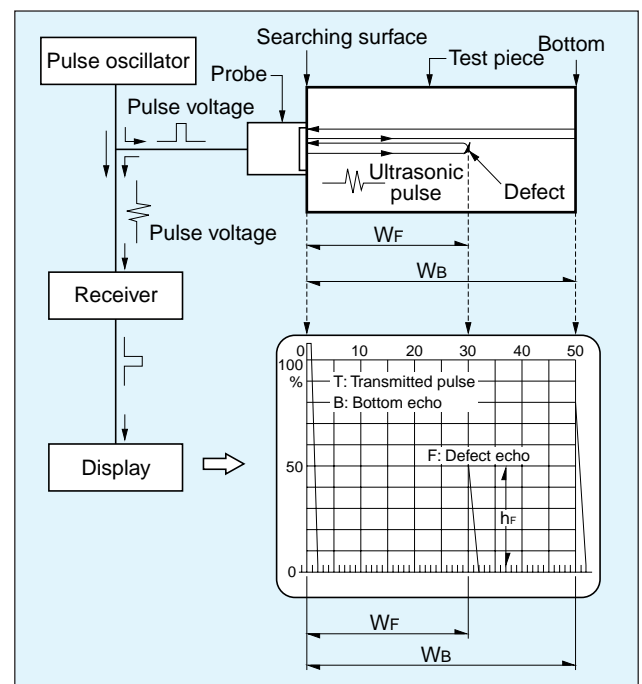


Fig. 6 Principle of ultrasonic testing

8. The ultrasonic microscope

The ultrasonic microscope can be used to test for defects and construction inside materials that could not be detected using optical or electron microscopes. This device can also make quantitative measurements of elasticity characteristics of micro regions.

Defects in materials destroy the strength of materials, cause wear of sliding materials, and cause peeling of coatings and joint surfaces. The Scanning Acoustic Microscope (S.A.M.) is an ultrasonic microscope suited to testing the surfaces of these materials. The S.A.M. focuses an ultrasonic beam at the test surface and mechanically makes a secondary XY scan. Fig. 7 shows an example of this system construction. The heart of the ultrasonic microscope is the ultrasonic focusing element using an acoustic lens at the upper right of the diagram. This is the sensor section. In general, the higher the ultrasonic frequency, the better the resolution, but ultrasonic attenuation increases with penetration into the specimen, effectively limiting the depth that observation is possible. Ultrasonic frequency is applied in a wide range from several dozen MHz to several GHz.

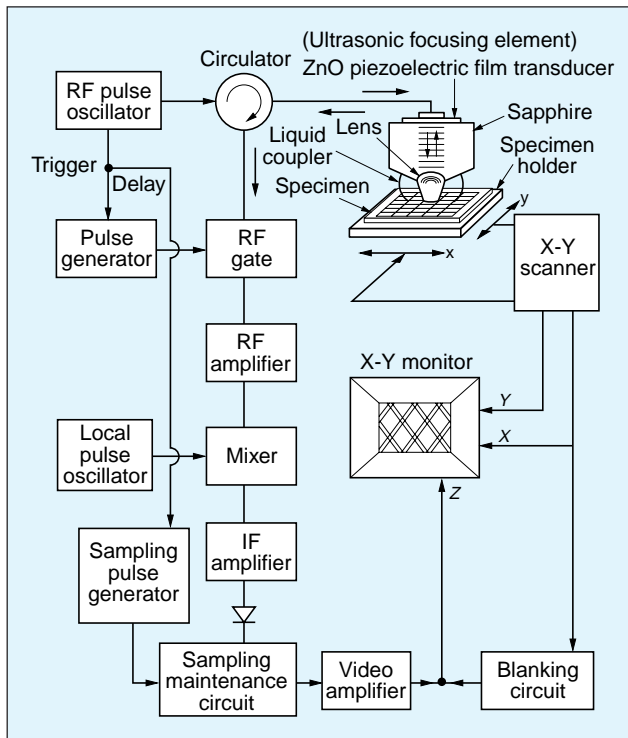


Fig. 7 Construction of mechanical scanning ultrasonic microscope

9. Electromagnetic induction (eddy current) testing

When alternating current is passed through a coil that is near a conductor, electromagnetic induction causes a circular current to be induced in the conductor as shown in Fig. 8. This is called an eddy current.

Eddy current has the property of generating magnetic flux that negates the alternating current magnetic flux of the coil. As seen in Fig. 9, when a flaw such as a crack in the surface of the conductor breaks the succession of the surface, the magnetic flux generated by the eddy current flow changes, and so the magnetic flux in the test coil changes, which appears as a change in the impedance of the test coil. Therefore, defects such as cracks in the surface of the metal can be detected from changes in the electromotive force of the coil.

Eddy current defect testing includes such features as high-speed, non-contact operation and ease of automation.

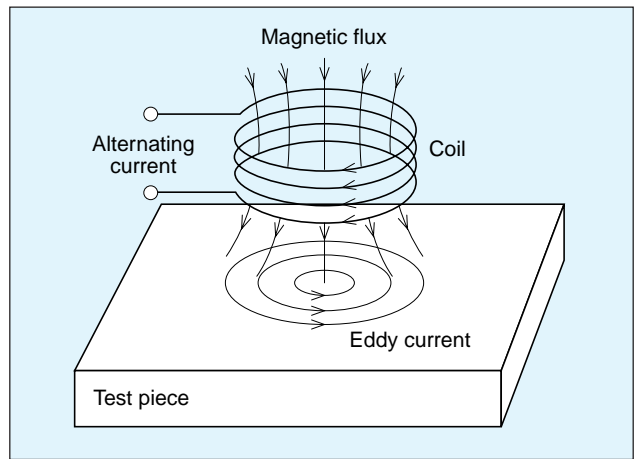


Fig. 8 Induction of eddy current

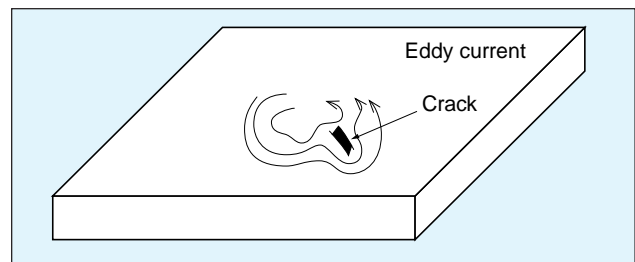


Fig. 9 Changes in the eddy current due to a crack

10. Conclusion

As symbolized by large system accidents these past few years, we are seeing a trend for accidents to create serious social problems. Because of this, the safety of products and facilities is a problem that cannot be bypassed by engineers involved in the field of manufacturing.

Product liability (PL) has become generally accepted to mean that the corporation bears responsibility for results of accidents in which safety is compromised by defects from the design and manufacture of products. Therefore, the importance of non-destructive measurement technology has been rapidly increasing. New research and development in this area can be expected to continue to flourish.

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