Properties of radiations

X-rays and gamma rays are electromagnetic radiations which have the following common properties.

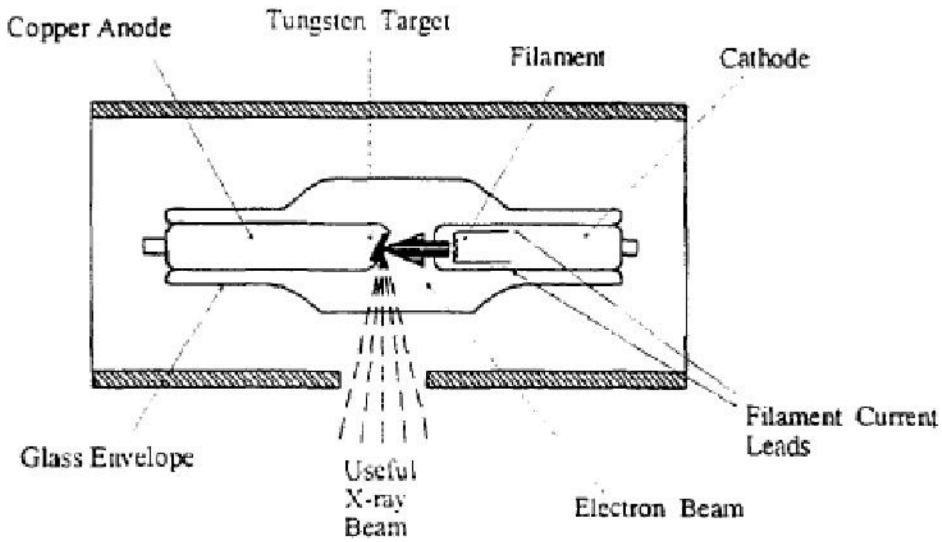
(i) They are invisible.
(ii) They cannot be felt by human senses.
(iii) They cause materials to fluoresce. Fluorescent materials are zinc sulfide, calcium tungstate, diamond, barium platinocyanide, napthalene, anthracene, stilbene, thalium activated sodium iodide etc.
(iv) They travel at the speed of light i.e. 3×10^{10} cm/sec.
(v) They are harmful to living cells.
(vi) They can cause ionization. They can detach electrons from the atoms of a gas, producing positive and negative ions.
(vii) They travel in a straight line. Being electromagnetic waves, X-rays can also be reflected, refracted and diffracted.
(viii) They obey the inverse square law according to which intensity of X-rays at a point is inversely proportional to the square of the distance between the source and the point. Mathematically I a $1/r^2$ where I is the intensity at a point distant r from the source of radiation.
(ix) They can penetrate even the materials through which light cannot. Penetration depends upon the energy of the rays, the density and thickness of the material. A monoenergetic beam of X-rays obeys the well known absorption law, I = Io exp (-ux) where Io = the incident intensity of X-rays and I= the intensity of X-rays transmitted through a thickness x of material having attenuation coefficient u .
(x) They affect photographic emulsions.
(xi) While passing through a material they are either absorbed or scattered.

Properties (vii), (viii), (ix), (x), (xi) are mostly used in industrial radiography.

Sources for radiographic testing

(i) X ray **machines**

X rays are generated whenever high energy electrons hit high atomic number materials. Such a phenomenon occurs in the case of X ray tubes, one of which is shown in above figure . The X ray tube consists of a glass envelope in which two electrodes called cathode and anode are fitted. The cathode serves as a source of electrons. The electrons are first accelerated by applying a high voltage across the cathode and the anode and then stopped suddenly by a solid target fitted in the anode. The sudden stoppage of the fast moving electrons results in the generation of X rays, These X rays are either emitted in the form of a cone or as a 360 degree beam depending upon the shape and design of the target. The output or intensity of X rays depend upon the kV and the tube current which control the number of electrons emitted and striking the target. The energy of X rays is mainly controlled by the voltage applied across the cathode and the anode which is of the order of kilovolts. The effect of a change in the tube current or the applied voltage on the production of X rays is shown in above Figure.



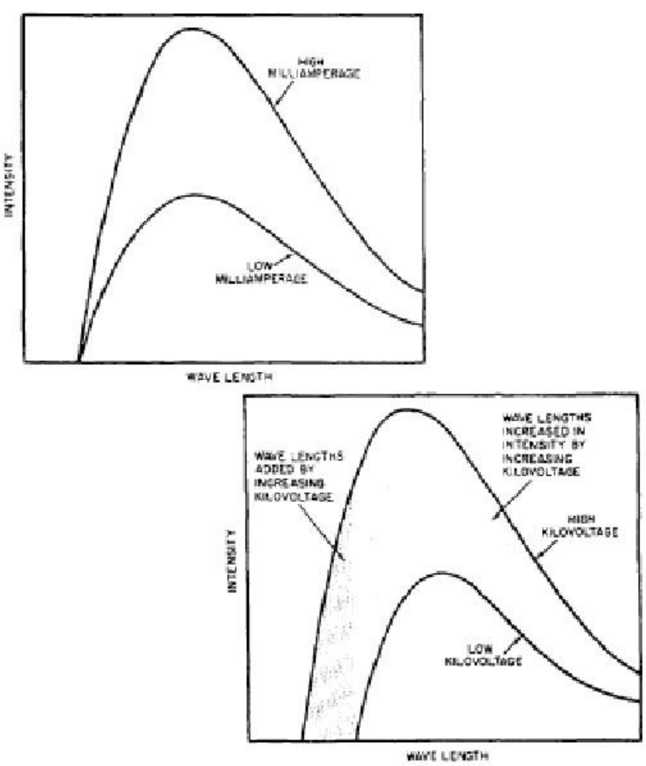


Figure : Effect of tube current (mA) and voltage (kV) on the intensity of X rays.

There is a variety of X ray machines available for commercial radiographic testing. Some of these emit X rays in a specified direction while others can give a panoramic beam. There are machines which have a very small focal spot size for high definition radiography. These are called micro focus machines. Some machines are specially designed to give very short but intense pulses of X rays. These are called flash X ray tubes and are usually used for radiography of objects at high velocity. Typically X ray machines of up to a maximum of about 450 kV are commercially available for radiographic testing.

(ii) Gamma ray sources:

These are some elements which are radioactive and emit gamma radiations. There are a number of radioisotopes which in principle can be used for radiographic testing. But of these only a few have been considered to be of practical value. The characteristics which make a particular radioisotope suitable for radiography include the energy of gamma rays, the half life, source size, specific activity and the availability of the source. In view of all these considerations the radioisotopes that are commonly used in radiography along with some of their characteristics are given in Table 3.1.

(iii) Radiographic linear accelerators:

For the radiography of thick samples, X ray energy in the MeV range is required. This has now become possible with the availability of radiographic linear accelerators. In a linear accelerator the electrons from an electron gun are injected into a series of interconnected cavities which are energized at radio frequency (RF) by a klystron or magnetron. Each cavity is cylindrical and separated from the next by a diaphragm with a central hole through which the electrons can pass. Due to the imposed RF, alternate diaphragm hole edges will be at opposite potentials at all times and the field in each cavity will accelerate or decelerate the electrons at each half cycle. This will tend to bunch the electrons and those entering every cavity when the field is accelerating them will acquire an increasing energy at each pass. The diaphragm spacing is made such as to take into account the increasing mass of electrons as their velocity increases. They impinge on a target in the usual way to produce X rays. Linear accelerators are available to cover a range of energies from about 1 MeV to about 30 MeV covering a range of steel thicknesses of up to 300 mm. The radiations output is high (of the order of 5000 Rad per minute) and the focal spot sizes usually quite reasonable to yield good quality radiographs at relatively low exposure times.

(iv) Betatron

The principle of this machine is to accelerate the electrons in a circular path by using an alternating magnetic field. The electrons are accelerated in a toroidal vacuum chamber or doughnut which is placed between the poles of a powerful electromagnet. An alternating current is fed into the energising coils of the magnet and as the resultant magnetic flux passes through its zero value, a short burst of electrons is injected into the tube. As the flux grows the electrons are accelerated and bent into a circular path. The magnetic field both accelerates the electrons and guides them into a suitable orbit and hence, in order to maintain a constant orbit,

TABLE 3.1 : TYPICAL RADIOACTIVE SOURCES FOR INDUSTRIAL RADIOGRAPHY

Characteristics / Source	Half life	Gamma ray energies (MeV)	RHM value per curie	Optimum thickness range (mm of steel)	Half value layer (mm of lead)
Thulium-170	128 Days	0.87, 0.52	0.0025	2.5 to 12	-
Cobalt-60	5.3 Years	1.17, 1.33	1.33	50 to 150	13
Iridium-192	74.4 Days	0.31, 0.47, 0.64	0.5	10 to 70	2.8
Caesium-137	30 Years	0.66	0.37	20 to 100	8.4

these two factors must be balanced so that the guiding field at the orbit grows at an appropriate rate. The acceleration continues as long as the magnetic flux is increasing, that is, until the peak of the wave is reached; at this point the electrons are moved out of orbit, either to the inner or outer circumference of the doughnut, by means of a DC pulse through a set of deflecting coils. The electrons then strike a suitable target. The electrons may make many thousands of orbits in the doughnut before striking the target, so that the path lengths are very great and the vacuum conditions required are in consequence very stringent. The radiation from betatrons is emitted in a series of short pulses. In order to increase the mean intensity some machines operate at higher than mains frequency. Most betatrons designed for industrial use are in the energy range of 6-30 MeV. Betatrons in general have a very small focal spot size typically about 0.2 mm, but the X ray output is low. Machines are built in the higher energy range in order to obtain a higher output, but this brings the disadvantages of a restricted X ray field size.

3.5.1.4 Films for radiographic testing

The detection system usually employed in radiographic testing is the photographic film usually called an X ray film. The film consists of a transparent, flexible base of clear cellulose derivative or like material. One or both sides of this base are coated with a light sensitive emulsion of silver bromide suspended in gelatin. The silver bromide is distributed throughout the emulsion as minute crystals and exposure to radiation such as X rays, gamma rays or visible light, changes its physical structure. This change is of such a nature that it cannot be detected by ordinary physical methods, and is called the latent image.

However, when the exposed film is treated with a chemical solution (called a developer) a reaction takes place causing the formation of tiny granules of black metallic silver. It is this base, that constitutes the image. Above figure is an expanded pictorial view of the general make up of afilm.

Radiographic film is manufactured by various film companies to meet a very wide diversified demand. Each type of film is designed to meet certain requirements and these are dictated by the circumstances of inspection such as (a) the part (b) the type of radiation used (c) energy of radiation (d) intensity of the radiation and (e) the level of inspection required. No single film is capable of meeting all the demands. Therefore a number of different types of films are manufactured, all with different characteristics, the choice of which is dictated by what would be the most effective combination of radiographic technique and film to obtain the desired result.

The film factors that must be considered in choosing a film are : speed, contrast, latitude and graininess. These four are closely related; that is, any one of them is roughly a function of the other three. Thus films with large grain size have higher speed than those with a relatively small grain size. Likewise, high contrast films are usually finer grained and slower than low contrast films. Graininess, it should be noted, influences definition or image detail. For the same contrast, a small grained film will be capable of resolving more detail than one having relatively large grains. The films are generally used sandwiched between metallic screens, usually of lead. These screens give an intensification of the image and thus help to reduce the exposure times besides cutting down the scattered radiation.

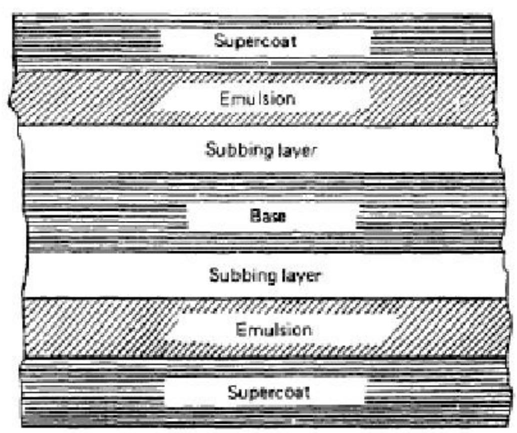


Figure : Construction of radiographic films

General procedure for radiographic testing

The test specimen is first of all properly cleaned and visually inspected and all the surface imperfections are noted. A properly selected film, usually sandwiched between intensifying screens and enclosed in a light proof cassette is prepared. The source of radiation, the test specimen and the film are arranged as shown in Figure 3.11. Image quality indicators and lead identification letters are also placed on the source side of the test specimen. From a previously prepared exposure chart for the material of the test specimen, the energy of radiations to be used and the exposure (intensity of radiations x time) to be given are determined. Then the exposure is made. After the source of radiation has been switched off or retrieved back into the shielding (in case of gamma ray source), the film cassette is removed and taken to the dark room. In the dark room, under safe light conditions, the film is removed from the cassette and the screens and processed. The processing of the film involves mainly four steps. Development reduces the exposed silver bromide crystals to black metallic silver thus making the latent image visible. Development is usually done for 5 minutes at 20°C. After development the film is fixed whereby all the unexposed and undeveloped crystals of film emulsion are removed and the exposed and image-forming emulsion is retained on the film. The fixing is done for approximately 2-6 minutes. The film is then washed preferably in running water for about 20-30 minutes and dried Finally the film is interpreted for defects and a report compiled. The report includes information about the test specimen, the technique used and the defects. It also sometime says something about acceptance or rejection of the reported defects. The report is properly signed by responsible persons.

Different forms of radiographic testing

(i) Fluoroscopy

In the general radiographic process, if the film is replaced by a fluorescent salt screen then the image of the test specimen can be visually seen. The X rays passing through the object excite the fluorescent material producing bright spots in the more heavily irradiated areas. The fluorescent screen may be viewed directly or by means of a mirror or by using a camera and a closed circuit television. The whole set-up of X ray tube, the test specimen and the fluorescent screen are encased in a protective shielding.

In many cases castings of up to about 10 mm thickness, thin metal parts, welded assemblies and coarse sandwich constructions are screened by this method and castings with obvious large defects are rejected before usual inspection using film radiography.

Plastic parts may be checked for the presence of metal particles or cavities. Other applications include inspection of electrical equipment such as switches, fuses, resistors, capacitors, radio tubes, cables and cable splices in which breaks of metal conductors, short circuiting or wrong assembly may cause troublesome electrical testing. Ceramics, fire bricks and asbestos products lend themselves perfectly to fluoroscopy. Packaged and canned foods are examined for the amount of filling and for the presence of foreign objects.

(ii) Micro radiography

Specially prepared thin samples are radiographed at extremely low energies (e.g. 5 KV) on an ultrafine grain film. The radiograph when enlarged gives the structural 92 details of the specimen. Micro-radiography is mainly applied in metallurgical studies.

(iii) Enlargement radiography

In some situations an enlarged image of an object is desired. To get the enlargement of the image the object to film distance is increased. To overcome the penumbral effects a source of an extremely small size is used.

(iv) High speed or flash radiography

For the radiography of moving objects, the exposure time should be very small and, at the same time, the intensity of the X rays should be extremely high. This is achieved by discharging huge condensers through special X ray tubes which give current of the order of thousands of amperes for a short time (of the order of a millionth of a second). This technique is normally applied in ballistics.

(v) Auto radiography

In this case the specimen itself contains the material in radioactive form. When a film is placed in contact with the specimen, an autoradiograph is obtained showing the distribution of the radioactive material within the specimen. The technique is mainly used in the field of botany and metallurgy

(vi) Electron transmission radiography

A beam of high energy X rays is used to produce photo-electrons from a lead screen. These electrons after passing through the specimen (of very low absorption like paper, etc.) expose the film and an electron radiograph is obtained.

(vii) Electron emission radiography

In this case a beam of X rays is used to produce photoelectrons from the specimen itself. These electrons expose the film which is placed in contact with the specimen. Since emission of electrons depends upon atomic number of an element, the electron emission will give the distribution of elements of different atomic numbers.

(viii) Neutron radiography

In this case a neutron beam is used to radiograph the specimen. The recording system will, therefore, not be a photosensitive film since it is insensitive to neutrons. The following methods are used to record the image:

(1) A gold foil is used which records the image, in terms of the activity produced. This image can be transferred onto

a film by taking an autoradiograph of the foil. Some other suitable materials such as indium and dysprosium can replace gold.

(2) The metallic foil upon neutron bombardment does not become radioactive but instead emits spontaneous gamma rays which expose the film placed in contact with it. Examples of metals suitable for this are lithium and gadolinium.

(3) Neutrons transmitted through the specimen are made to strike a thin neutron scintillator plate. The scintillations thus produced expose the film which is in contact with the scintillator.

In certain cases neutron radiography is advantageous as compared to X or gamma radiography, for example:

(a) If the specimen is radioactive.
(b) If the specimen contains thermal neutron absorbers or light elements.
(c) Two elements whose atomic number is not very different may be easily distinguished.

(ix) Proton radiography

For special type of studies a proton beam can also be used. The number of protons transmitted through a specimen whose thickness is close to the proton range is very sensitive to exact thickness. This helps in detecting very small local variations in density and thickness.

(x) Stereo radiography

Two radiographs of the specimen are taken from two slightly different directions. The angle between these directions is the same as the angle subtended by the human eyes while viewing these radiographs. In the stereo viewer the left eye sees one radiograph and the right eye the other. In this way a realistic three dimensional effect is obtained giving the visual assessment of the position of the defect.

(xi) Xeroradiography

This is considered as a "dry" method of radiography in which a xerographic plate takes the place of X ray film. The plate is covered with a selenium powder and charged electrostatically in the dark room. Exposure to light or radiation causes the charge to decay in proportion to the amount of radiation received and a latent image is formed.

The developing powder is sprayed on the plate in a light-tight box. The particles are charged by friction while passing through the spray nozzle. White powders have best contrast with the black selenium surface but present problems in transferring the picture to paper. Coloured powders on transfer produce negative images while fluorescent powder gives the same picture as white powder and can be viewed under black light both before and after transfer.

3.5.4 Personal safety and radiation protection

Nuclear radiations are harmful to living tissues. The damage done by radiations is sinister as human senses are not capable of detecting even lethal doses of radiation. The dose of radiations absorbed by human body is expressed in mSv (1 mSv = 100 rem = U/kg) which takes into account the biological effectiveness of different types of radiations such as alpha particles, gamma rays, X rays and neutrons, etc. The overall outcome of exposure to radiation is initiated by damage to the cell which is the basic unit of the organism. The effects of radiation may be deterministic or stochastic, early or late, of somatic or genetic type.

Somatic effects depend upon three main factors.

(a) First of these factors is the rate at which the dose is administered. Cells begin the repair processes as soon as some degree of damage has been received. When the body is able to keep up with the damage, no injury or pathological change will be seen in the irradiated individuals. However, the same amount of radiation given all at once would produce a more severe reaction.

(b) The second is the extent and part of the body irradiated. It is known that certain cells are more sensitive to radiation than others. Hence the overall effect of radiation depends on the extent and part of the body irradiated.

(c) The third important factor is the age of the affected individual, persons growing physically are in an accelerated stage of cells reproduction and most of the cells in the body are dividing and hence sensitive to radiation. For this reason an exposure of a given amount should be considered more serious for a young person than for an adult.

The somatic effects can either be immediate or delayed. Given below is a summary of immediate effects when the whole body is acutely irradiated with a range of radiation doses:

3.5.5 Applications of radiographic testing method

Radiographic testing is mainly applied for the detection of flaws such as cracks, porosity, inclusions, lack of root penetration, lack of fusion, laps, seams, shrinkage, corrosion, etc. in weldments and castings, in pressure vessels, containers for industrial liquids and gases, pipelines, steel bridges, steel and aluminium columns and frames and roofs, nuclear reactors and nuclear fuel cycle, boiler tubes, ships and submarines, aircraft and armaments. In most of these cases weld inspection is involved. Welds in plates are tested using an arrangement more or less similar to the one shown in above Figure 3. However, there are a number of different techniques for inspection of welds in pipes. These are illustrated in Figure 3.15. The welds in small diameter pipes are inspected usually using source-outside film-outside technique . Medium diameter pipes may also be inspected as in above Figure where source-inside-film outside technique is utilized. When the diameter of pipes becomes large enough, the circular welds may be examined using a panoramic technique. In this the source is placed at the centre inside the pipe and the film is wrapped all around the weld on the outside. Thus in this case the whole weld can be radiographed in a single exposure while for all other situations in above figure multiple exposures are required for full coverage.

Radiography is also extensively used for the inspection of castings and forgings. The regular shaped and uniformly thick specimens can be inspected as usual like welds in plates while special considerations need to be made for testing of specimens of varying thickness. Double film technique is usually employed wherein two films of different speeds are used for a single exposure. In this way correct density is obtained under the thick sections on the faster film whereas the slower films record correct images of the thin sections.

Radiography is used in inspection of explosives contained within casings, sealed boxes and equipment. In the field of electronics it is employed for the inspection of printed circuit boards and assemblies for checking adequacy of connections.

3.5.6 Range and limitations of radiographic testing

Radiographic testing method is generally applicable for the inspection of all types of materials, e.g. metallic, non-metallic and plastics, magnetic and non-magnetic, conductors and non-conductors, etc. as long as both sides of the test specimen are accessible for placement of source and the film on either side. The film needs to be placed in contact with the specimen and whenever this is not possible due to the geometry of the test specimen, radiographs of poorer quality will result.

The penetration of the radiation through the test specimen depends upon its thickness and density. For high density materials, as well as for larger thickness of the same material, higher energies are needed. Although, in principle, these higher energies are now available from betatrons and linear accelerators, these sources of radiation are extremely expensive and therefore not available for common use. Table 3.1 shows that among the commonly available radiation sources including the commercial X ray machines of up to about 420 KV, the strongest source is that of cobalt-60 which can be used for radiography of steel of thickness up to about 150 mm.

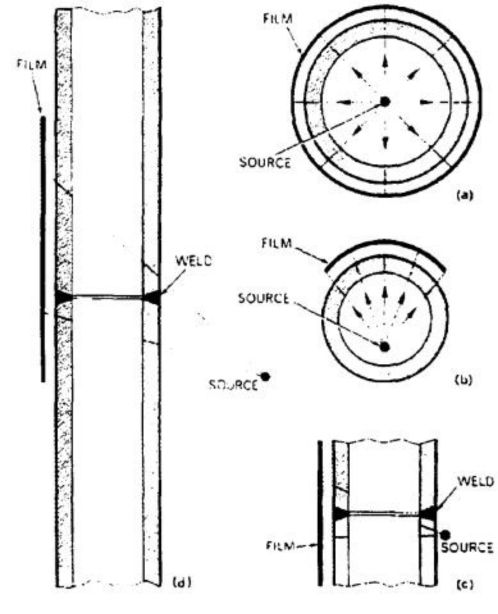


Figure 3.15: Various techniques for weld inspection.

The factors affecting radiographic quality and consequently the sensitivity of flaw detection by radiographic testing method need to be carefully considered while selecting the technique for a particular test. For example, for high sensitivity or to be able to detect smaller flaws, it is recommended that largest possible source-to film distance is used with a source of the smallest possible dimensions, the slowest and fine-grained film should be used and film processing should be done as per recommendations of the manufactures (usually for 5 minutes at 20°C). The lowest energy compatible with the thickness and density of the test specimen should be chosen. In practice a compromise has to be made between these ideal requirements to achieve an optimum level of sensitivity. But a radiograph made with a technique of poor sensitivity will need a more critical inspection, since defect images will not be so easily seen and may in fact be missed. There is a definite tendency to make a more cursory examination when defect images are only faintly seen. Similarly very small defects below the sensitivity limits of the technique employed may be missed. Such a situation can also arise due to improper viewing conditions and the training and experience of the interpreter. Sensitivity of flaw detection decreases with an increase in thickness of the test specimen.

Radiographic picture is a two-dimensional shadow of a three-dimensional defect. The orientation of the defect with respect to the direction of the beam is therefore an important consideration. Thus planar defects such as cracks, laminations, lack of fusion in welds or similar defects may not be detected if their plane is at right angles to the incident beam. Elongated defects like pipes and wormholes may show up and be misinterpreted as spherical defects. Smaller defects located behind the larger ones in the direction of the beam will not be detected.

A serious limitation with the radioisotope sources used for radiography is the fact that even unused their activity decreases with time. While they have the distinct advantage of needing no power for field radiography applications, they need special shielded enclosures to house them and the radiographic sensitivity achievable with them is usually inferior to that for X rays.

Lastly, exposure to radiations can be dangerous for human health and therefore special precautions are required which may include construction of specially shielded enclosures and cordoning off of the area where radiography is being performed. Mostly it involves either stopping of all other work and removal of the workers from the work place while carrying out radiography or to do the radiographic testing work during off hours.

UNIT –IV

ADVANCED TECHNIQUES – I

Phased array use in the industry. **Phased array** is widely used for **nondestructive testing** (**NDT**) in several industrial sectors, such as construction, pipelines, and power generation. This method is an advanced **NDT** method that is used to detect discontinuities i.e. cracks or flaws and thereby determines component quality.

Phased array ultrasonics (PA) is an advanced method of ultrasonic testing that has applications in medical imagingand industrial nondestructive testing. Common applications are to noninvasively examine the heart or to find flaws in manufactured materials such as welds. Single-element (non-phased array) probes, known technically as *monolithic* probes, emit a beam in a fixed direction. To test or interrogate a large volume of material, a conventional probe must be physically scanned (moved or turned) to sweep the beam through the area of interest. In contrast, the beam from a phased array probe can be focused and swept electronically without moving the probe. The beam is controllable because a phased array probe is made up of multiple small elements, each of which can be pulsed individually at a computer-calculated timing. The term *phased* refers to the timing, and the term *array* refers to the multiple elements. Phased array ultrasonic testing is based on principles of wave physics, which also have applications in fields such as optics and electromagnetic antennae.

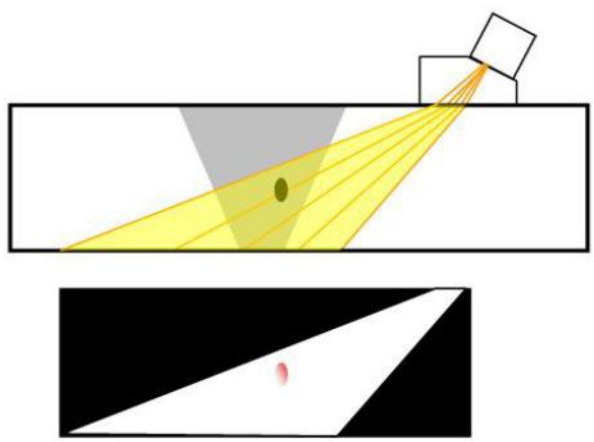


Fig: Weld examination by phased array.

Principle of operation:

The PA probe consists of many small ultrasonic transducers, each of which can be pulsed independently. By varying the timing, for instance by making the pulse from each transducer progressively delayed going up the line, a pattern of constructive interference is set up that results in radiating a quasi-plane ultrasonic beam at a set angle depending on the progressive time delay. In other words, by changing the progressive time delay the beam can be steered electronically. It can be swept like a search-light through the tissue or object being examined, and the data from multiple beams are put together to make a visual image showing a slice through the object.