Non-destructive Evaluation of Welds - An Overview

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INTRODUCTION

Non destructive testing as the name implies, is the technology of assessing the soundness and acceptability of a weld, casting or an actual component without affecting the functional properties of the component. Non Destructive Evaluation (NDE) has become an inseparable part of modern society. Be it the field of engineering, technology, or healthcare, NDE is being used right from cradle to the end of service to optimize processes, manage quality, predict the life and limit liability. While NDE science and technology was qualitative during the first half of 20th century, the liberalisation of economies, reduced margins of safety and stringency of specifications during the second half of the 20th century has spurred the development and growth of quantitative NDE. Measurements form the heart of inspection and quantitative NDE. By making the right measure-ments at the right points and at the right time in the product life cycle, where it can support the most significant decisions i.e. the specifications used to ensure fitness for purpose, one can ensure excellence in quality and global product acceptability.

Welding is one of the most widely used methods for joining of metals. In spite of the numerous advances in the art and science of welding, failures do occur and welds continue to be considered as a weak link. The history of weld inspection can be traced to the discovery of X-rays in 1895 by Sir William Conrad Roentgen. With the advent of ASME Boiler and Pressure Vessel Code in 1915 and the successful application of X- and gamma rays by Lester in 1920, weld inspection using ionising radiations gained prominence. It was only after the World War II that conventional NDE methods assumed prominence and importance of weld inspection was realized by the industries. With the advent of fracture mechanics concepts in the late 1970s and the need to know the size and shape of the defects, non destructive testing graduated from a "go" - "no go" technique to a evaluation technique providing quantitative data. This was greatly possible due to the advances in sensors, imaging and image processing capabilities.

While a number of advanced NDE techniques have evolved, the backbone of routine weld testing is still the domain of conventional NDT methods - namely Visual, Dye Penetrant, Magnetic particle, Eddy Current, Radiography and Ultrasonics. Of these, visual, radiography and ultrasonics are outlined below due to their applicability in practically all the cases and their wide spread utility. The advances in these methods are also discussed. While weld inspection after the welding is completed is still the mainstay, online weld monitoring has the advantages with respect savings in inspection time and man-hours.

Visual Testing

Visual testing is the first and foremost NDE method for weld inspection used by inspectors world over and for more than 95% of welds made each day. The main advantage of visual inspection is that it is easy to apply, quick, relatively inexpensive and requires no special equipment. Visual inspection of welds is carried out in three stages:

1. Pre-weld Visual Inspection
2. Visual Inspection during Welding
3. Post-weld Visual Inspection

Pre-weld Visual Inspection:

This inspection is conducted before the actual welding operation. It is primarily associated with ensuring the adequacy of weld joint preparation and verification of parameters that would be difficult or impossible to confirm during or after welding. Visual inspection prior to welding is one of the best way to prevent defective welds. Joint preparation is the main area for which visual inspection can be applied during pre-weld stage.

Joint preparation involves dimensional inspection of root gap, checking groove weld bevel angles and joint alignment. Too small root gap is the cause for inadequate root penetration while large

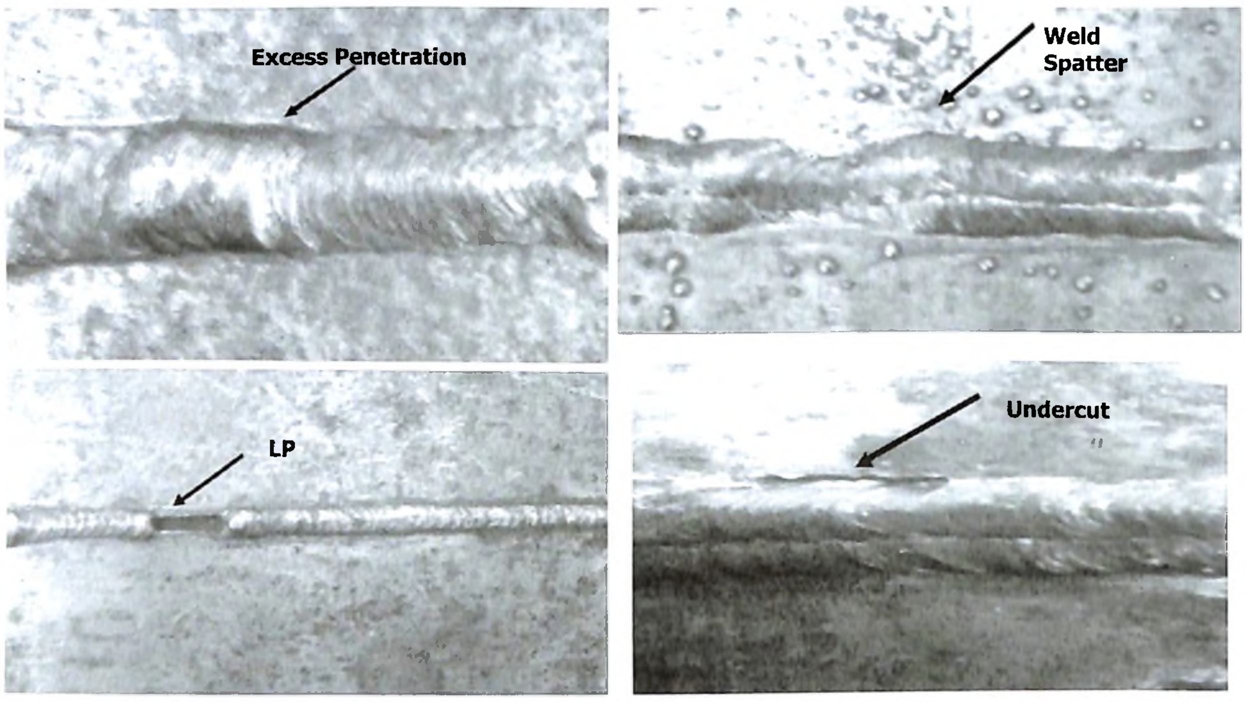

Fig. 1 : Typical welds discontinuities detected during post weld visual inspection

root gaps can lead to excess penetration. Small groove weld bevel angles may cause lack of fusion while too large a bevel angle can result in distortion of the weld joint due to overheating. Misalignment of joints can be a cause of distortion and stress concentration, resulting in a reduction of fatigue life. In addition, an inspector is also required to ascertain the plate surface condition. Improper or inadequate cleaning or presence of corroded areas can result in unacceptable levels of porosity / inclusions etc. A good pre-weld inspection provides the Inspector and the Fabricator an excellent opportunity to prevent many welding problems.

Visual Inspection during Welding

This inspection includes application of visual examination to ensure adequacy of interpass cleaning, interpass temperature control, welding current settings, welding travel speed, shielding gas type, gas flow rate, and welding sequence etc. Inspection during the welding operation can help us to detect defects such as slag, lack of penetration and ensure corrective situations before they can escalate. Visual inspection during welding increases the confidence in the welded product.

Post-weld Visual Inspection

This is the final stage in which the NDE inspector verifies the integrity of the completed weld. It is during this stage, that many of the commonly occurring welding discontinuities such as undercuts, weld spatter, excess penetration, overlap, surface cracking, surface porosity, under fill, incomplete root penetration and burn through are detected Post-weld Inspection is the final stage of determining the weld's acceptability primarily with respect to surface discontinuities and also weld appearance. Figure 1 shows some of these discontinuities.

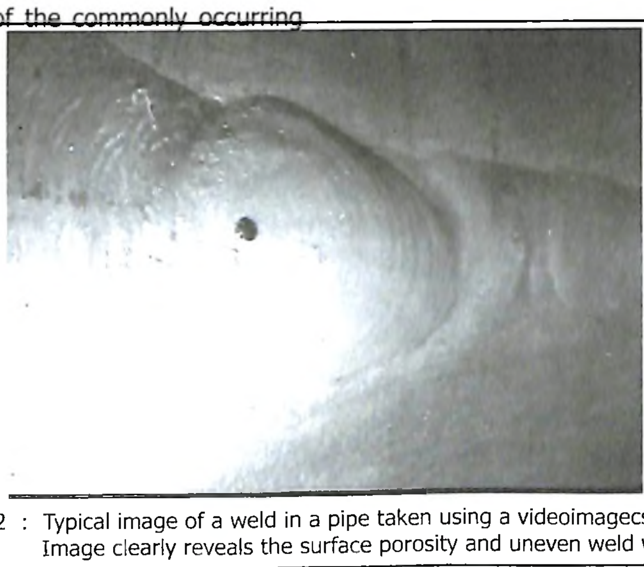

Fig. 2 : Typical image of a weld in a pipe taken using a videoimagecsope. Image clearly reveals the surface porosity and uneven weld width.

Visual Inspection Tools

During visual inspection, the tools that are normally used include magnifying glass, flash light and special weld gauges. These are adequate for general weld inspection. However for in service inspection, special equipments such as Borescopes, Fiberscopes and video-scopes are being used. A borescope is an optical device consisting of a rigid or flexible tube with an eyepiece at one end and an objective lens at the other end with a number of intermediate lenses. Images of the interiors of the objects can be viewed clearly but no quantitative measurements can be accomplished. Borescopes have limited lengths. A fiberscope on the other hand consist of an eyepiece at one end and a lens at the other, interlinked through a fibre optic bundle. Normally two fibre optic bundles are present. One bundle is a coherent bundle for image formation and the other is an incoherent bundle used for light transmission (illumination of region of interest). The lens is often a wide-angle lens, and the eyepiece can be connected to a through a monitor or a PC. Videoimagescope is a fiberoscope with a difference that instead of fibre optic bundles with lens for image formation, a CCD image sensor is used in the tip. Videoscopes have excellent RESOLUTION and image CLARITY. Both fiberoscope and videoimagescope have the possibility of 2-4 way articulation of the tips to view internally inaccessible areas. Figure 2 shows a typical image of a weld as seen through a viedoimagescope. The surface porosity can be clearly seen.

Visual inspection is the simplest, most effective but widely underestimated and under utilised NDE method. Visual inspection can only locate defects on the weld surface. Specifications or applicable codes may require that the internal portion of the weld and adjoining region also to be free from unacceptable discontinuities. In such cases, NDE methods such as radiography and ultrasonics are used, which are described below.

RADIOGRAPHIC TESTING OF WELDS

Radiography is one of the most widely used methods for weld inspection. It is based on the principle of differential absorption of penetrating radiation such as X-rays and gamma rays by the object under test. The detector is normally a sheet of photographic film that on exposure to X- or gamma rays and subsequent development provides a grey level image. The amount of X-rays and gamma rays absorbed / attenuated within a material depends on the density and composition and thus a radiograph is used to reveal discontinuities and inclusions within the opaque material. The radiographic film is a permanent record that provides the basic information by which weld soundness can be ensured.

Radiographic testing can provide a permanent film record of weld quality that is relatively easy to interpret by trained personnel. This testing method is usually suited to objects with access to both sides of the welded joint. It is the best suited NDT method for volumetric defects such as porosity, inclusions and voids and linear indications such as lack of penetration and lack of fusion. Cracks can also be detected if the radiation beam is properly aligned. While in general, defect depth measurement is difficult from a single radiograph, techniques based on double exposure parallax method and also step wedge based calibration has been evolved. It is essential that qualified personnel conduct radiographic interpretation since false interpretation of radiographs can seriously interfere with productivity and safety. X-rays and gamma rays are hazardous and hence personnel carrying out radiography should be qualified and certified and ensure that they follow all safety precautions.

Over the years, evolutionary changes have occurred both in sources and detectors. We have today mini and microfocus X-ray sources and a host of recording devices. Microfocal radiography has been reviewed in detail in ref.1. We describe below the develop-

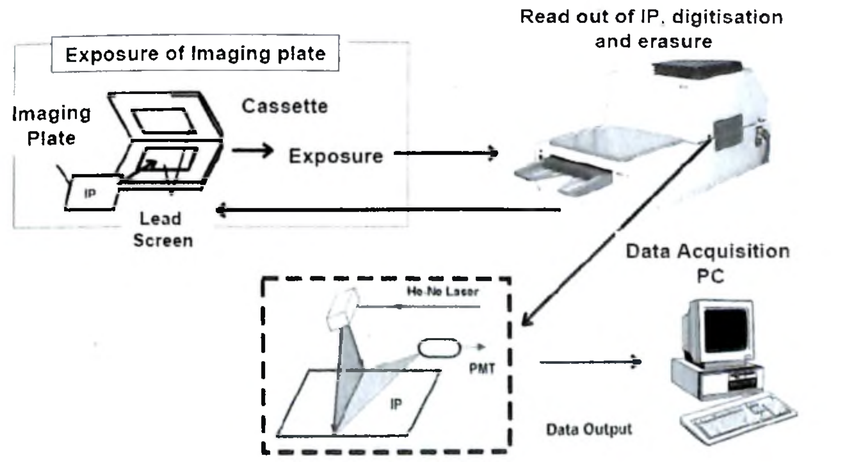

Fig. 3 The Computed Radiography Process
Courtesy : Dr Uwe Ewert and Dr Uwe Zscherpel, IAEA presentation

ments in the area of detection which has led to the advent of digital radiographic imaging.

Digital Radiography

Computed Radiography or Filmless Radiography

The evolution of industrial radiographic imaging towards totally digital imaging has accelerated over the past decade with the advent of computed radiography and image intensifier / flat panel based real time radiography. Since its introduction, two decades ago in the medical field, computed radiography (CR) has now slowly entered into the industrial domain and is becoming a main player in acquiring, processing and displaying digital images. CR is a process of delivering images that is similar to conventional screen/film system. The main difference between the two systems is that CR processes the optical signals based on a phenomenon called "photostimulated luminescence", rather than from a prompt emission of electrons, as in the case with screen-film radiography.

In CR, instead of the film, an imaging plate containing a storage phosphor is sandwiched between the lead screens and inserted in a cassette similar to a screen-film system. It is then, exposed to x-rays. The imaging plate (IP) contains photostimulable storage phosphors, which store the radiation level received at each point in local electron energies. The imaging plate is fed into a laser scanner which scans the plate using a laser beam. The scanning laser beam causes the electrons to relax to the ground state emitting light that is detected by a photo-multiplier tube, which is then converted to an electronic signal. The electronic signal is then converted to discrete (digital) values which are displayed on the monitor. The digital image can be viewed and enhanced using digital image-processing software, such as contrast, brightness, filtration and zoom. This is schematically illustrated in Fig. 3 below.

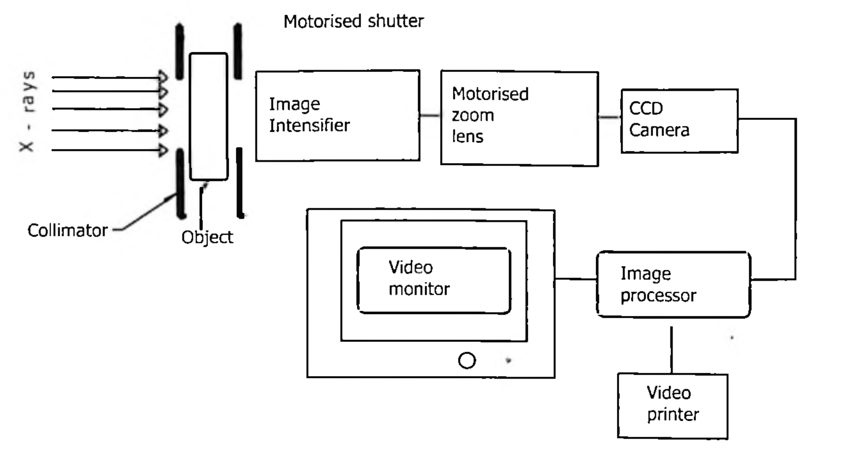

Fig. 5 : Block Diagram of real time radiography setup

Figure 4 shows a typical CR image of a weld plate taken by the authors. The CR image clearly indicates cracks which is a measure of the achievable sensitivity.

The main advantages of CR include

1. Shorter exposure time (10-40 % of Film).
2. Higher Dynamic Range which means greater thickness latitude leading to decreased number of exposures.
3. Reusable Phosphor plates – About 1000 times and better when handled with care.
4. No chemicals for processing – eco

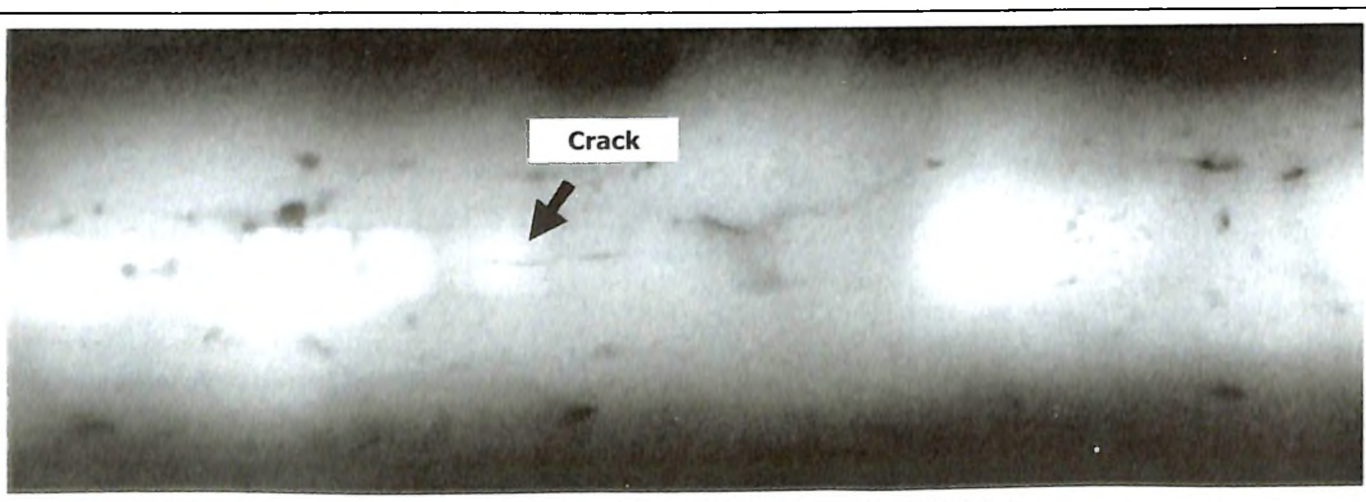

Fig. 4 Computed Radiographic Image of Stainless Steel Weld Pad

Fig. 7 Processed Radiographic Image acquired using Flat Panel Detector of Stainless Steel Weld Pad. A 80 micron wire penetrameter can be seen. Note the sharp radiographic contrast and good detail visibility.

friendly and consumable cost saving.

5. Entire image processing takes less than 5 minutes which means more exposures possible.
6. Faster defect evaluation & decision.
7. Direct Digital Archiving.

Real Time Radiography

Real time radiography (RTR) differs from conventional film radiography in that the X-ray image of the object is observed directly on a screen rather than recorded on a film. The advent of image intensifier tubes in the 1950s led to the development of real time radioscopy systems which overcame all the problems of fluoroscopic systems. Present day real time systems use image intensifiers, video camera and monitor. The image intensifier converts X-ray photons to electrons, accelerates the electrons and then re-converts them to light which is picked up by the CCD camera and displayed on a monitor. Figure 5 shows the block diagram of a typical RTR setup.

The RTR system essentially consists of an image intensifier tube, a zoom lens, CCD camera, image processor and a monitor. When a beam of X-rays is incident on the input screen of the image intensifier, the X-ray photons are converted into light photons by the detector – Caesium iodide. A photo-cathode converts the light photons to electrons which are accelerated and impinge on the output phosphor. The output phosphor converts the electrons to light photons which are picked up by the CCD camera and after image processing displayed on the TV monitor.

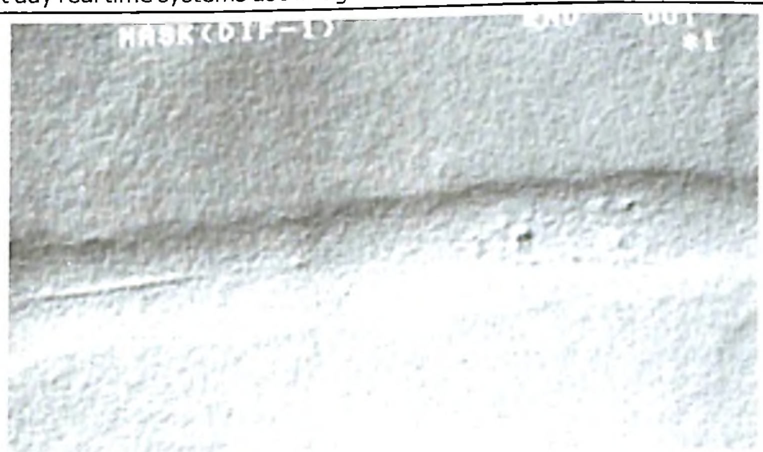

Fig. 6 Real time edge enhanced image of a weld with lack of penetration and porosities

The main advantages of RTR include an overall savings both with respect to man-hours spent, cost and archiving the radiographic image. Accept-or-reject decisions can be made immediately without the delay in film development. This has been found to be cost effective in the long run. Limitations of RTR are its higher inherent screen unsharpness, which limits the overall radiographic sensitivity as compared to that of film radiography. However, through the use of image processing, the sensitivity levels can be improved to those obtainable in film radiography.

Figure 6 shows a typical real time image of a weld with lack of penetration and porosities. RTR is presently applied to objects on assembly lines for rapid inspection. It finds extensive applications in real time evaluation of automotive components such as wheel castings, valves, and online inspection of seam welds, canned foods and in a variety of other industries.

Digital Real Time Radiography of Welds using Flat Panel

Flat panel detectors, also called Digital

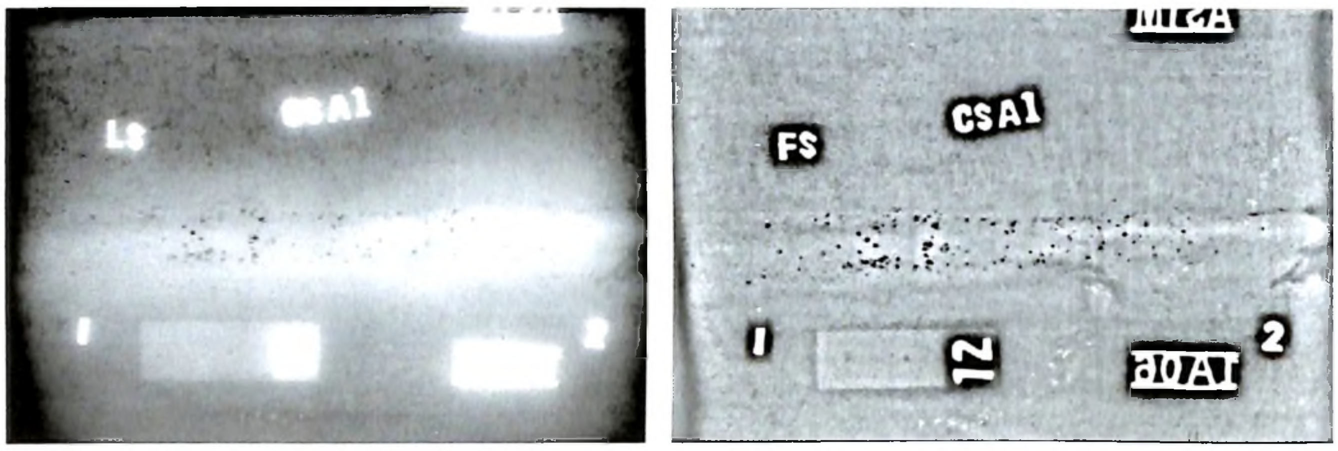

Fig. 8 : Radiographic Image of a weld (a) Raw image after Brightness and Contrast Enhancement (b) Image after application of High Pass filter. Note that wire penetrameter and 2T hole in IQI is very clearly seen after enhancement.

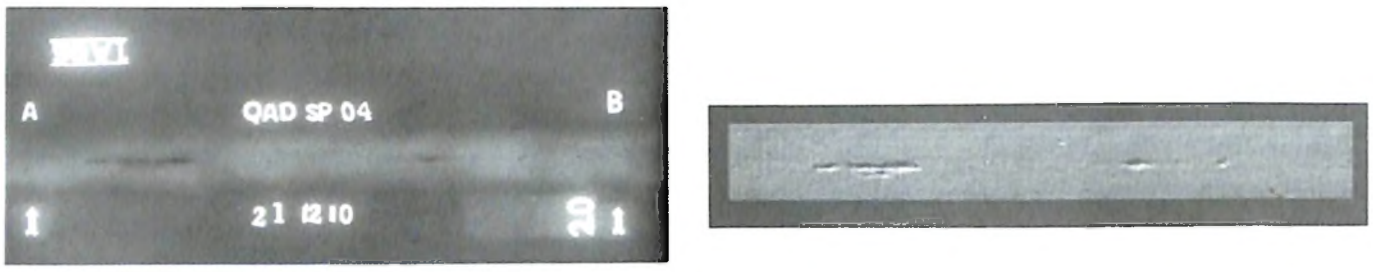

Fig. 9 Left radiographic image of a weld revealing lack of penetration. Right is a edge enhanced image of the weld region. Edge enhancement makes it possible to measure the defect dimensions more accurately.

Detector Arrays (DDA) are becoming an alternative technology for both, computed radiography and image intensifier based real time radiography. These detectors are mostly based on amorphous silicon arrays with thin film transistors for read out control and photo diodes as light detectors. The photodiodes are covered with a fluorescent screen for light conversation. A recent addition is the development of detector systems which have a direct conversion process. Amorphous selenium or CdTe-systems belong to this category of detectors. Compared to the indirect conversion systems, direct conversion systems have better spatial resolution and better signal to noise ratio. Flat panels are recent additions in digital radiography. They are very good substitutes to film radiography and image intensifier based systems and well suited for the application of computed tomography (CT). They allow fast, reliable and cost effective inspection and are much more sensitive. Fig. 7 is a typical weld image obtained using a conventional X-ray source and flat panel detector of a weld. The cracks on the surface can be seen very clearly. The main limitations of these panels are – they need to be operated in temperature controlled atmospheres and are not flexible. They also have limited life times. However, such panels are finding increasing applications in shop floors. Tailor made systems are being used in the industries for automated defect recognition in long seam weld etc.

Image Processing for Enhanced Weld Inspection

An important advantage of Computed Radiography and the real time systems described above is that the images can be in digital form making it amenable to image processing and analysis. Image processing as the name implies is the application of algorithms to enhance the perception of potential defects. Typically the first step in image processing is the adjustment of contrast and brightness functions to obtain an optimum image. After this, the image is subjected to a variety of spatial filters to enhance the sensitivity and also defect detectability. Fig. 8 and Fig. 9 below presents three typical cases of application of filters.

Today image processing finds wide

applications for improving the signal to noise ratio and also enhances detectability of defects. A variety of filters are available for denoising and transforms such as Hough are being adopted for delineating the defect boundaries an essential step towards automated defect recognition.

ULTRASONIC TESTING OF WELDS

In this inspection method, high frequency sound waves are sent into the object under test. The sound waves travel through the material. During their path of travel they suffer loss of energy and are reflected at interfaces. A receiver probe picks up the reflected wave and an analysis of this signal is done to locate flaws in the object under inspection. Sound waves follow the laws of optics in their propagation. Further, the velocity of propagation of sound in various metals has been very accurately determined. The time taken by a sound pulse to travel through a material is a direct measure of the length of path travelled by it. In ultrasonic inspection, both through transmission and pulse-echo techniques are used. Most of the ultrasonic inspection is done in the mega cycle range at frequencies between 0.5 and 25 MHz which is well above the audible range. The probes used for ultrasonic inspection contains a piezo-electric crystal. The transmitter probe generates ultrasonic pulses and transmits them into the materials while the receiver probe receives the reflected pulses.

The principal advantages of ultrasonic inspection as compared to other methods for nondestructive inspection of welds include :

- Ability to test welds with single sided access
- Can be used on ferrous and non-ferrous welds and most suited for testing thicker sections (~ upto 400 mm has been tested by the authors lab)
- High sensitivity permitting the detection of extremely small flaws and also enhanced detectability of planar flaws such as cracks which are difficult to detect in radiography.
- Provides flaw sizing and orientation which is difficult to get with other NDE methods.
- Volumetric scanning ability, enabling the inspection of the complete volume of metal extending from front to back surface of the weld
- It is not hazardous to operators or other nearby personnel.
- It is portable and can be used in fields with batteries. It can also be interfaced to computers to allow for digital signal processing.

A main requirement of UT is that this testing method requires a high level of operator training and competence and is dependant on the establishment and application of suitable testing procedures. Two of the most important advances in the field of ultrasonic testing is the phased array and time of flight diffraction. These are outlined below.

Phased Array

Conventional ultrasonic transducers consist of either a single active element that both generates and receives high frequency sound waves, or two paired elements, one acting as a transmitter and the other as receiver. Phased array probes typically consist of a transducer assembly with from 8 to as many as 256 small individual elements. While having all the flexibility of conventional transducers, the main advantage of a phased array probe is that it can sweep a sound beam through a range of refracted angles or along a linear path, or dynamically focus at a number of different depths.

The unique advantages of phased array as compared to conventional pulse echo technique include :-

1. Use of multiple elements to steer,

Fig. 10 Inspection of outer shell weld of SG using phased array

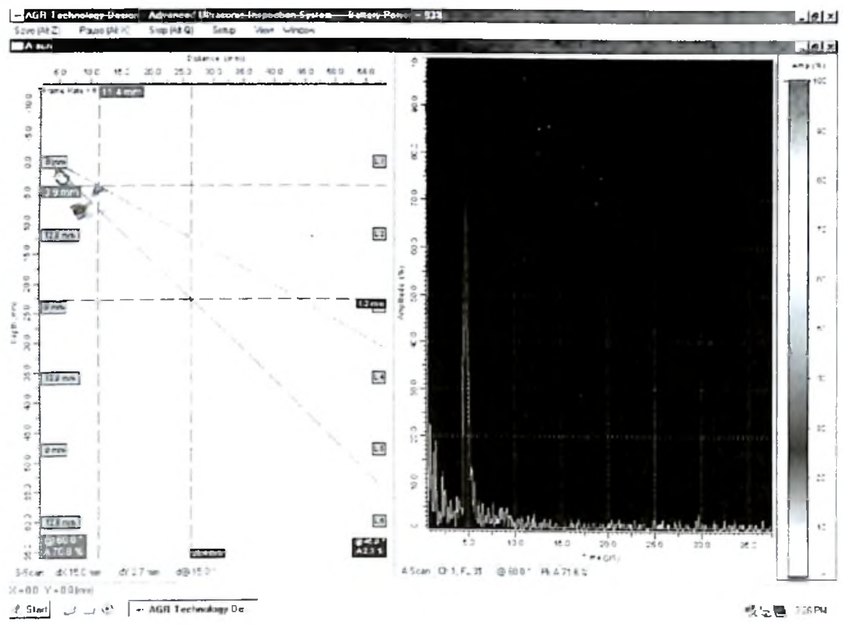

Fig. 11 Typical S-Scan and corresponding A-Scan image of Lack of fusion in the steam generator.

focus and scan beams with a single transducer making it possible to completely cover the weld region with a single probe. This sectorial scanning greatly simplifies the inspection of welds with complex geometries.

2. The ability to test welds with multiple angles from a single probe further enhances the defect detectability.
3. Electronic focusing permits optimizing the beam shape and size at the expected defect location and also improving the signal to noise ratio, thus aiding in detection of defects that would have been otherwise missed in pulse echo technique.
4. The ability to focus at multiple depths also improves the ability for sizing critical defects.

At the author's laboratory, phased array technique is being widely used for practically all critical applications. Examinations of welds in vent pots, dissolver vessels, tanks and air receivers are typical applications. Two recent applications are described below.

Steam generators are the workhorse in a nuclear power plant. The Steam Generator of Prototype Fast Reactor being fabricated at M/s. Larsen and Tubro Works Powaii is a vertical, countercurrent shell and tube type heat exchanger with Sodium on shell side, flowing from top to bottom and water/steam on the tube side. The very high reactivity with Sodium with water makes the Steam Generator a key component in determining the efficient running of the plant and demand high integrity of Steam Generator weld joints. Advanced ultrasonic testing techniques like Phased array has been applied to evaluate the shell side 12 mm thick butt welded joints, as a part of quality audit. A total weld length of 6 m from various seams was subjected for ultrasonic examination. The phased array probe used was of 5 MHz 16 element. Sectorial beam scanning with 45° (minimum) and 65° (maximum) was used. During scanning, a distance of 10 mm was maintained between the wedge front face and weld centre line to cover the full volume of the weld. The weld was scanned from the top and bottom side. For 1 m length of weld, the total scanning and evaluation time with conventional UT is apprx. 2.1 hrs while in the case of phased array, the inspection could be completed in 50 mins. Apart from the drastic reduction of scanning and evaluation time, Phased array technique also detected defects that could have been missed in conven-

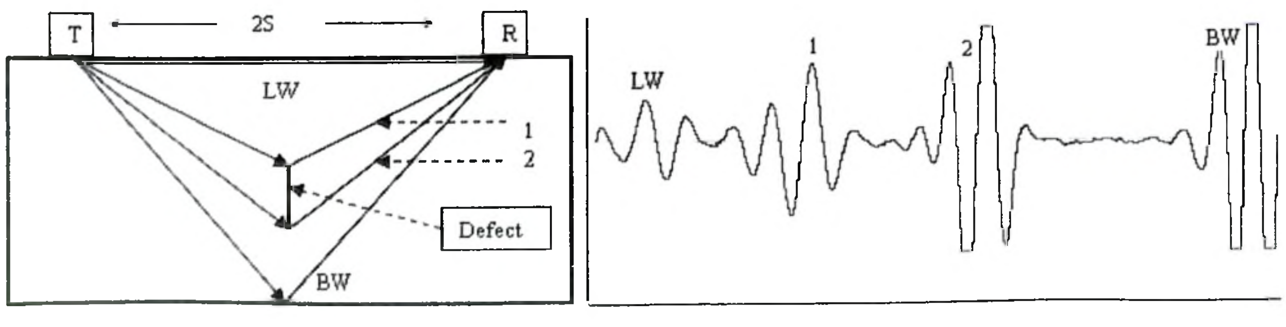

Fig. 12 : Typical TOFD arrangement and A-Scan display

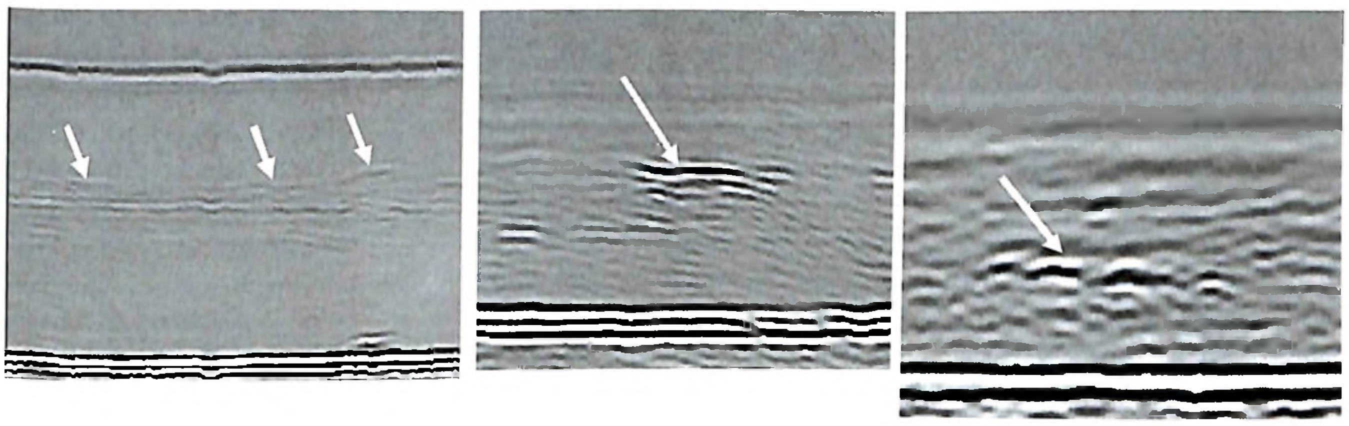

Fig. 13 Typical TOFD images of defects in welds. (a) Lamellar tearing (b) Lack of Penetration (c) Lack of fusion

tional UT. Figure 10 shows the Phased array examination on the outer shell weld while Fig. 11 is the typical sectorial scan with a lack of fusion detected by Phased array.

Apart from nuclear applications, at the author's lab, the technique has also been applied to aerospace industry for examination of Maraging steel rocket motor casings and in process industries for examination of tanks.

Time of Flight Diffraction

While pulse echo ultrasonic techniques are well established, time-of-flight diffraction (TOFD) technique is a relatively new ultrasonic imaging method which is slowly gaining acceptance for thick walled weldments. Conventional pulse echo or phased array are techniques based on the reflection of signals while time of flight diffraction as the name implies is based on the principle of measurement of time of flight of the diffracted echoes that are generated from the top and bottom tips of a defect or discontinuity when a longitudinal wave is incident on it [2,3]. The main advantages of TOFD compared to pulse echo UT and RT are:

(a) Rapid scanning is possible and weldments can be scanned in single pass making this technique more efficient and faster.

(b) Discontinuity size and depth can be very accurately determined. Since the technique is based on the detection of diffracted signals, it is not affected by the orientation of the discontinuity and angle of examination.

(c) Longitudinal angle beam being used by TOFD makes it possible to examine thick austenitic stainless steel weldments.

(d) Real time discontinuity monitoring is possible and the data can be stored for further reference and analysis.

A typical probe set up for TOFD and the corresponding amplitude (A-scan) signal is shown in figure – 12. Two longitudinal beam transducers of same angle are used in a pitch catch configuration in which one probe acts as a transmitter and the other one as a receiver. The longitudinal bulk wave which travels just under the surface from the transmitter to the receiver, called lateral wave (LW), and the back wall (BW) echo are used to define the region of interest (thickness of the specimen). Additional signals appeared in between LW and BW are the diffracted ultrasonic waves from the (1) top and (2) bottom tips of the discontinuity.

By knowing the transit time between these diffracted echoes, the depth and size of the discontinuity can be obtained by solving simple trigonometric relations. TOFD is a well developed technique and has been applied successfully for accurate sizing of defects in thick sections (>12mm). Codes of practice such as ASME now permit TOFD for routine inspection as one of the method for an alternative to radiography. At the authors laboratory, TOFD is being applied on a routine basis for inspection of welds of tanks and vessels in service. Fig. 13 shows a typical lack of penetration and lamellar tearing detected in welds.

An innovative application of TOFD has been for the evaluation of thin walled weldments (~ 3mm) by combining it with immersion technique. Immersion coupling provides a delay line, variable angles and necessary probe separation making it possible to examine the lower thickness successfully [4].

CONCLUSIONS

NDE is an inseparable part of the welding industry. This article outlines the widely used conventional NDE methods that are being utilised for the inspection of welds. The benefits of dedicated visual inspection of welds has been specifically highlighted. Apart from providing the readers with an overview of ultrasonic and radiography techniques, an attempt has also been made to elucidate the advanced NDE techniques in both these methods. The objective of this article has been to educate and kindle the spark in the readers on the various proven advanced techniques for which detailed literature is available. The techniques that have been indicated can be applied for weld inspection in practically all the industries to enhance and ensure the safety, reliability and quality of welds.

ACKNOWLEDGEMENTS

The authors thank Shri S. C. Chetal, Director, Indira Gandhi Centre for Atomic Research, Kalpakkam for his constant encouragement and support. The authors are indebted to Dr. Baldev Raj who has always been a source of inspiration and whose constant mentoring has been responsible for the innovations in NDE. The authors also thank all the staff members of Quality Assurance Division for their support. The authors are grateful to Mr. Pabitra Das of IIW-India and Dr. D. K. Bhattacharya, former Deputy Director (Retd) of CGCRI for providing this opportunity.

REFERENCES

1. Baldev Raj and B.Venkatraman, Practical Radiography, Narosa Publishers, 2007.
2. J.A. G. Temple, "Time-of-flight inspection: theory", Nucl. Energy, 1983, 22, No. 5, Oct., 335 – 348.
3. J.P. Charles worth, J.A.G. Temple, Engg. Application of ultrasonic Time of flight diffraction, 2nd ed. Research Studies Press Ltd., 2001.
4. R.Subbaratnam, Saju Abraham, Sukumar Manna, B.Venkatraman and Baldev Raj, Immersion and TOFD (I-TOFD): A Novel Combination for Examination of Lower Thicknesses, Journal of Non Destructive Evaluation (In press).

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