Nondestructive Testing of Welds

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The present day engineering industry relies heavily on welded components and structures. Therefore, weld integrity becomes important for adequate and reliable performance of components, structures, and plants. Weld integrity is dependent on the quality of base material and welding process. It is widely accepted that testing, measurement, and control of welds should be optimized based on fitness-for-purpose (FFP) approach, taking into account the welding processes and economical aspects of ensuring the desired levels of reliability. High technological demands have been met by recent advances in materials technology and by the availability of better and more reliable test techniques for ensuring the desired quality.

A discontinuity is an interruption of the typical structure of a weldment, and it means lack of homogeneity in the mechanical, metallurgical, or physical characteristics of the material or weldment. Weld discontinuities can be classified broadly as cracks, cavities, slag inclusions, incomplete fusion or penetration, imperfect shape or unacceptable contour, and other miscellaneous discontinuities such as spatter, arc strikes, etc.

Nondestructive Testing (NDT)

NDT is an integral and the most important constituent of the quality assurance (QA) program of any industry. The objectives of the QA programs are safety, productivity, reliability, and economy. Nondestructive evaluation places due emphasis on characterization of materials including quantitative determination of the size, shape, and location of a discontinuity or abnormality assessment thus enabling evaluation of structural integrity of a component particularly in the context of fitness for purpose. NDT, along with material properties and operating conditions, is vital for successful prediction of damage and residual life.

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Quality characteristics of welds having discontinuities such as cracks, inclusions, porosity, lack of penetration, lack of fusion, lack of bond, and undercut and alloy identification can be evaluated by NDT methods. The present range and capabilities of NDT techniques promise evaluation of weld joints for the most stringent service conditions. However, proper choice of materials, welding processes, etc. is a necessity to ensure building the quality in the product. Choice of a technique or complementary techniques should be carefully made to ensure structural integrity during designed life of welded structures on a cost effective basis. Various NDT methods can be employed to evaluate a welded component depending upon the material, thickness, sensitivity requirement, accessibility for inspection, etc. Nondestructive testing over the years, in combination with operational experience, has led to well established testing practices all over the world.

This article describes various conventional NDT techniques and advancements that have taken place in these techniques for evaluation of welded components to the required quality level.

Visual Inspection

Visual and optical testing (VT) is probably the most widely used among the nondestructive tests. For welds, this is all the more important as at various stages of welding, visual inspection gives useful information unparalleled in value as compared to any other nondestructive test methods. Many characteristics of a weld can be evaluated by visually examining a completed weld, but much can be learned by observing the weld as it is being made. For many noncritical welds, integrity is verified principally by visual inspection. Even when other nondestructive methods are used, visual inspection still constitutes an important part of quality control. Visual inspection should be done before, during, and after welding.

Many visual aids are available to enhance the inspection, ranging from a pocket magnifier to microscope and monochromatic illumination to CCD camera color video presentation. Intrascopes (rigid or flexible) are available to permit entry and inspection of internal surfaces through access openings (of less than 1 mm [0.04 in.]) so that the NDT inspector is able to link and extract a wealth of primary NDT results from visual inspection. The convenience of visual aids is ergonomically desirable to reduce fatigue and improve reliability.

Liquid Penetrant Testing

Liquid penetrant testing (PT) is another NDT method to detect surface discontinuities and also subsurface discontinuities

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open to surface in welded materials. This method can be used in root pass and subsequent passes to detect surface discontinuities so that repair work can be undertaken at the earliest stage in welding sequence to remove the discontinuities in the weld.

This method is best adopted to inspect all types of surface cracks, porosity, laminations, and lack of bond at exposed edges or joined materials and leaks in welded tubes and tanks. It has been used with significant success for weldments of ferrous and nonferrous materials, ceramics, glass, as well as some plastics and synthetic materials.

Magnetic Particle Testing

For detection of surface and subsurface discontinuities in welded components, liquid penetrant testing and magnetic particle testing (MT) are being widely used. In the case of ferromagnetic materials, magnetic particle technique has been preferred since this will also detect subsurface anomalies that are not open to surface. Because of this advantage over liquid penetrant testing, it has become customary to specify magnetic particle testing for all ferromagnetic materials. To get the highest sensitivity, fluorescent magnetic particles suspended in oil using full wave DC continuous technique are employed.

Many weld discontinuities are open to the surface and are readily detectable by magnetic particle testing using prods and yokes. For detection of subsurface discontinuities, such as slag inclusions, voids, and inadequate joint penetration at the root of the weld, prod magnetization is considered the best, using alternating current, direct current, or half wave current. The detectability of subsurface discontinuities in butt welds, made between relatively thin plates, can be improved by positioning a direct current yoke on the side opposite the weld bead. Magnetic particles are applied along the weld bead. Improvement is achieved because of the absence of extraneous leakage flux that normally emanates from the yoke's pole pieces.

The composite magnetization method is an advancement in MT. The method requires magnetization of the work piece longitudinally with an alternating electromagnet wound with a secondary coil. The induced electromotive force on the coil produces a large short circuit current on the work piece to magnetize circularly that part of the work piece which is being inspected. When the longitudinal and circular magnetic fields match each other, a composite magnetic field will be formed so that surface cracks oriented in any direction can be detected simultaneously.

Systems are available with automatic crack detection with computer vision and pattern recognition of magnetic particle indications. An example is a connecting rod crack detection system that is a computer vision based system with multiple solid state video cameras. The rod is passed through magnetic particle solution and then scanned in front of a camera. The video image is digitized and fed into a microcomputer. The computer analyzes the image to detect crack indications based on their linearity and geometry properties. The preimage processing and digital image processing techniques make automation of fluorescent magnetic particle inspection a viable plant operation tool. These techniques are employed for inspection of fluorescent crack indications for a variety of welded parts.

Eddy Current Testing

Eddy current testing (ET) is based on the principle of electromagnetic induction and is used to identify or differentiate between a wide variety of physical, structural, and metallurgical conditions in electrically conductive materials and metal parts. This method does not require direct electrical contact with the part being inspected. The eddy current method is adaptable to high speed inspection and can be used to inspect an entire production, if so desired. This possibility is due to high speed inspection capability of this technique. The method is based on indirect measurement and the correlation between the instrument readings and the structural characteristics, thus the acceptability of the parts being inspected must be carefully established with high reliability.

ET has been successfully used to locate discontinuities like lack of fusion, incomplete penetration, cracks, oxidation, and changes in chemical composition and hardness of welds. One of the difficulties in using ET is that the instruments are sensitive to so many variables that careful adjustments must be made to measure the desired weld properties without interference from noncritical characteristics. Many improvements in the latest electronic instruments have made ET equipment suitable for evaluation of production welds.

For the inspection of ferromagnetic products, a direct current magnetic saturating coil is located concentrically around the primary energizing coil. The direct current coil is energized at high current levels to magnetically saturate or partially saturate the object in the inspection zone. This improves the penetration of the eddy currents and minimizes the effect of magnetic variables. In the case of pipe weld inspections, this type of inspection is effective in detecting most types of longitudinal weld discontinuities such as open welds, weld cracks, penetrators, and pin holes due to circumferential orientation of the eddy current flow.

This technique in its conventional form has a few limitations for inservice inspection though it meets the requirements for inspection during manufacture and preservice stages. The limitations during ISI are interference from support structures, less sensitivity for circumferential cracks in a tubular structure, inspection of ferromagnetic materials, and lack of methodologies for accurate discontinuity characterization. In order to overcome the above limitations, a number of developments have taken place, making ET more versatile, reliable, and fast. The developments have come in the form of computer models, instrumentation for multifrequency, phased array, remote field, imaging, development of special probes, and development towards automation in testing. With the help of these advancements, significant progress has been made with respect to discontinuity detection and characterization.

Ultrasonic Testing

There are two aspects that distinguish ultrasonic testing (UT) of welds from UT of other products, like forgings, castings, pipes, etc. — the area of interest is defined and limited (weld and heat affected zone), and a specific set of discontinuities whose probable location and orientation are known. Most welds fall into one of the following categories: butt weld, tee weld, or nozzle weld. Weld discontinuity sizing is done by either 6 dB or 20 dB drop method.

Welds of certain materials such as austenitic stainless steel and nickel based alloys of thickness greater than 10 mm (0.4 in.), pose serious problems for ultrasonic testing. These problems are primarily due to the acoustic anisotrophy of these materials and the cast structure of the weld. Heavy scattering of the ultrasonic beam, false indications, and wrong judgment of position and size of the discontinuity can be encountered in these materials. This results in heavy attenuation of the beam as well as noise signals reaching the probe. The combined effect of these results is the loss of sensitivity and low signal to noise ratio. These problems are greatly minimized by the utilization of longitudinal wave angle beam probes for such applications. It is a well known fact that compressional waves are attenuated less than shear waves. Also, in the case of scattering, the scattered waves contain a lesser proportion of longitudinal waves than shear waves. These two facts put together lead to the conclusion that use of longitudinal wave angle beam can considerably improve the signal to noise ratio. This has been tried successfully and such longitudinal wave angle beam probes are now commercially available. It has also been reported that attenuation is minimum when the longitudinal beam is inclined at 45 degrees to the grain axis and this can be taken advantage of during testing. However, one has to guard against indications due to the shear wave component that always accompanies refracted longitudinal wave component.

Another improvement is the use of double crystal angle beam probes. Since double crystal probes (both normal beam and angle beam) focalize the beam to a narrow band of material thickness, other parts of the weld do not interfere in the testing. This results in enhanced signal-to-noise ratio. Obviously probes with different focalization depths will have to be used for the same weld to cover the entire thickness.

In conventional UT, only one parameter

of the reflected signal, namely amplitude, is studied. In the case of austenitic welds it is difficult to depend upon or even measure this single parameter because of poor signal to noise ratio. Hence additional parameters of the signal, such as frequency spectrum content, can give reliable information. Signal analysis by correlation techniques has been attempted with various degrees of success. However, it must be realized that signal processing needs a careful validation for ensuring consistent reliability and enhanced sensitivities.

A major application of synthetic aperture focusing technique (SAFT) is to characterize the discontinuity for quantitative evaluation and to enable application of fracture mechanics based concepts for estimation of the remaining life of a welded component. In this method, analysis of the received ultrasonic signals is accomplished by one of two methods. First, it can be done by stationary methods where, at fixed probe positions, all the echoes from a discontinuity, direct as well as satellite echoes, are compared with the results of calculated or measured echoes of typical discontinuities (modeling). Secondly, this can be done by moving the probe along the surface and picking up the echoes for all probe positions and thus synthesizing an aperture. This technique gives resolution of the order of a wavelength independent of the range of the discontinuity and has been successfully used as a discontinuity sizing method for testing welded components.

The time of flight diffraction technique (TOFD) has the ability to capture high resolution, to detect low amplitude signals, and to perform real time processing to carry out crack tip diffraction. The major advantage of the TOFD mode of operation is the on line graphic (D-Scan) display of inspection data. This presents the operator with a real time radiographic type image, representing a through wall section along the weld axis with discontinuities shown in their true length and accurate sectional location and size. Making use of the search and sizing capability of TOFD, by Silk et al. at Harwell have brought about a number of developments in increasing the ability of the technique to study welds in thick steel sections and have developed a system for field use.

The general test procedure followed for preservice and inservice inspection of reactor pressure vessels is the use of 0 and 70 degrees longitudinal wave probes, 45, 60, and 70 degrees transverse wave inspection with single and T-R (SE) probe technique as well as the Tandem technique. These techniques employ a large number of transducers in a multiprobe arrangement. The possibility of replacement of most of these probes by an optimized linear array has been explored by Fraunhöfer Institute for NDT (IzfP), Germany. Because of the high flexibility due to the electronic steering feature, the advantages of the linear array probe are obviously twofold — reduction in preparation time, and amelioration of the system performance with regard to discontinuity detection and discontinuity analysis. With linear array probes, the sound field can be steered in one plane, and the field parameters are determined by the geometry of the active area of the probe perpendicular to this plane.

In the case of complicated shapes of the components, for example, inspection of the perforated area, it may be necessary to steer and focus the ultrasonic beam not only in one plane but three dimensionally at the bottom and top portions of pressurized water reactors. The inspection of the web and the weldments requires the variation of the angle of incidence, the focus depth, and the orientation to the plane of incidence. The optimal solution to this problem is a planar array. For the computerized design and optimization of linear and planar array probes, extensive software packages have been developed.

Accidental discovery in 1967 that electromagnetic radiation can excite acoustic resonances in single crystal discs of Bi and Al at liquid helium temperatures without making any contact to samples and with apparently strong coupling to the conduction of electrons in the crystals led to a number of investigations on the properties of electromagnetic acoustic transducers (EMAT) and their application to NDT. Significant progress has taken place in the last three decades and a variety of inspection problems were elegantly solved by the use of EMATs, among others, worth mentioning are the inspection of moving, hot objects, and the difficult to inspect anisotropic welds.

EMATs are the devices that essentially consist of a stack of wires and magnets to excite and detect ultrasonic waves in an electrically conductive material, be it magnetic or nonmagnetic. When an EMAT transmitter is placed near, but not necessarily in contact with, an electrically conducting material, ultrasonic waves are launched in the material through the reaction of induced eddy currents and static magnetic fields. This eliminates the problems associated with acoustic coupling to the metal part under examination because the electromechanical conversion takes place directly within the electromagnetic skin depth of the metal. Thus, EMATs allow operation without contact at elevated temperatures and in remote locations.

Two major limitations in using EMATs for a number of practical applications are the physical size of the source of magnetic field (~20 mm [~0.08 in.]) and the low transduction efficiency (due to weak Lorenz and magnetostrictive driving forces) as compared to piezoelectric transducers. However, with the availability of high energy product rare earth magnets, it is now possible to construct small and highly sensitive EMATs.

Radiographic Testing

Radiographic testing (RT) is one of the most widely used NDT methods for the detection of internal discontinuities such as porosity and voids. With proper orientation, planar discontinuities can also be detected with radiography. It is also suitable for detecting changes in material composition, thickness measurement, and locating unwanted or substandard components hidden from view in an assembled part.

Generally, by radiography, one can recognize the nature of a discontinuity and also measure its effective length and width parallel to the plane of the film, but the through thickness dimension (height) is less easy to determine. The distance of a discontinuity from the surface can be found by stereometric methods. In principle, it is possible to measure the height of the discontinuity from the density of the image on the radiograph using a microdensitometer. The densities determined from the microdensitometer trace can be converted into thickness either by absolute calculations using the film characteristics and exposure curves, or by having an appropriate step wedge on the radiograph along side of the object and in the case of weldments near the weld.

It is reported that, for general weld discontinuities occupying 10 to 30 percent of the thickness, this method can be applied with an accuracy ranging from 3 to 8 percent. Discontinuities such as porosities, lack of fusion, lack of penetration, voids, inclusions, etc. in the welds and hot tears and shrinkage cavities in the castings can be easily detected by radiography. The detectability of cracks by radiography is influenced by the position and size of the crack, the incident angle of X-rays, the distance between the film and the crack, size of the focal spot, sensitivity of films, and screens. A good amount of work has been done on crack delectability and sensitivity. Conventional radiography is being widely used for the inspection of a variety of weldments, castings, and complete assemblies in various industries.

High resolution radiography has been developed for better definition of discontinuities and delectability of small discontinuities like microcracks in jobs having thin sections and complex geometries. This is more so in the present context of the use of high technology manufacturing processes like laser welding and electron beam welding which has led to drastic reduction in component sizes and have consequently necessitated detection of smaller discontinuities.

Advancements in electron optical systems, vacuum technology, and computer controlled parameter optimization and monitoring techniques have made X-ray generators of very fine focus and smaller sizes of anode tubes available for industrial radiography. Advantages of such systems compared to conventional radiographic systems are:

- Fine focal spots (15 µm [5.9×10^{-4} in.]) give advantages like higher resolution, higher contrast, and the possibility of large magnifications.
- Rod anode X-ray heads are available

with small sizes (diameter of 6 mm [0.23 in.] onwards and lengths between 0.1 to 1 m [0.3 to 3.3 ft]) which facilitate panoramic radiography of smaller diameter pipe welds and radiography of complex joints like tube to tube sheet weld joints.

- High resolution of the discontinuity of the order of 25 μm (9.8×10^{-4} in.) using direct enlargement is possible, which facilitates radiography of thin objects and use of large film to object distances.
- Specially shaped anodes give a variety of X-ray emission modes for panoramic, radial backward or forward throw of X-rays, and directional throw of X-rays for varied applications.
- Easy adaptability for on line fluoroscopy.

Main limitations of this technique are the maximum voltage (225 kV) and maximum current (3 mA), which restrict thickness of objects to be radiographed to 3 mm (0.12 in.) of steel equivalent. The equipment is not portable like conventional X-ray equipment and has restricted use for inservice applications.

LINAC accelerates electrons using radio frequency voltages. These voltages are applied so that the electrons reach an acceleration point in the field at a precise time. The accelerator guide consists of a series of cavities which causes gaps when the radio frequency power is applied. The cavities have holes in each end which allow electrons to pass to the next cavity. When an electron is injected at the proper time, it gains energy as it is accelerated across these gaps. Proper phasing of the radio frequency power is essential for accelerators.

Recent developments in LINAC include portable machines with energies up to 16 MeV and radiation output up to 100 Gy/min (10 000 rads/min) at 1 m (3.3 ft) from the target. Increased operating frequencies up to 9300 MHz permit lightweight X-ray head. In the newer configuration of portable sets, it is possible to operate the accelerator and the collimator away from the radio frequency source using a flexible waveguide. Total weight of X-ray head is thus reduced, permitting easy positioning for inspection of welded pipelines, valves, and other components with limited accessibility. Radiography of steel up to 500 mm (20 in.) is possible with LINACS, which produce better radiographs than any other high energy equipment for steel thicker than 100 mm (3.9 in.).

Any image on a film or a screen can be scanned with a closed circuit television camera with a digital output and stored on a magnetic tape or disk as a number of pixels. A pixel array of 512 x 512 elements with 256 brightness levels on each pixel meets most of the industrial requirement for weld inspection. Once stored as digital pixel data, the image is available for computer enhancement techniques such as contrast stretching, edge enhancement, special filtering, differentiation, averaging, pattern recognition, etc. Online monitoring of welding is another possibility arising out of real time radiography. The versatility of image processing is that this can be performed in real time as well as on film images. This technique suffers from limitations of enhancement of the image noise as well to some extent, the limited dynamic range and contrast characteristics of conventional TV cameras which result in a loss of image quality during its acquisition from the film/screen.

Acoustic emission testing (AE) is used during inservice inspection of installed welded vessels and for online weld monitoring during fabrication. AE has been successfully used for online monitoring of welds prepared by TIG, submerged arc, electroslag welding, etc. This technique finds application as a complementary technique for inspection of critical areas in important installations. The discontinuities that can be detected and quantitatively evaluated by AE monitoring during welding are weld cracking associated with phase transformation, nucleation and growth of cracks during welding and subsequent cooling such as delayed cracking, porosity and slag inclusions, micro fissuring, hot and cold cracking, and reheat cracks.

Thermal imaging is employed for on line quality assessment of welding process. It is possible to identify arc misalignment, lack of penetration, etc., using infrared and thermal testing (IR) during welding.

Intelligent welding, as the name implies, combines welding equipment with intelligent sensing and control, knowledge of human experts, and artificial intelligence to improve joining efficiency. Occurrence of weld discontinuities can be reduced by developing smart or intelligent welding machines. A small welding machine is the one equipped with sensors, artificial intelligence, and actuators to sense and control welding operations in real time. Intelligent sensing and control is a multidisciplinary approach that attempts to build adequate sensing capability, knowledge of process physics, control capability, and welding engineering into the welding system so as to make the welding machine able to analyze the state of the weld and know how to correct the processing necessary to make good welds.

In the context of welding, *in situ* metallography is a very useful technique to ensure quality welding. Many times, preheating and postweld heat treatments are employed for ensuring stress-free weld joints. In the weld and interface regions, there could be dilution and alteration in the chemistry thus leading to formation of different microstructural features, some of which can be undesirable for example intermetallics in steels. The microstructural features of the weld joint decide the mechanical properties and thus its inservice performance. *In-situ* metallography can be usefully employed for determining the microstructure and thereby ensuring the fitness for purpose of the weld joint.

Conclusion

Nondestructive testing plays a crucial role in early detection of discontinuities and the subsequent follow-up remedial measures during various inspection stages of welded components to assess their structural integrity. NDT is also usefully employed to ensure reliable performance of welded components in service. A judicious choice is necessary to use a relevant or a combination of techniques to have cost effective and sound solution to quality assessment.

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