Reliable and Relevant Non-Destructive Measurements for Robust Technologies

Baldev Raj and B.Venkatraman
Indira Gandhi Centre for Atomic Research
Kalpakkam – 603 102, India

1.0 Introduction

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 tomb to optimize processes, manage quality, predict the life and limit liability avoiding accidents. 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 measurements 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.

The Indira Gandhi Centre for Atomic Research (IGCAR) located at Kalpakkam, Tamil Nadu, India is the second largest research centre of the Department of Atomic Energy (DAE) with the primary mission to conduct a broad based multidisciplinary programme of scientific research and advanced engineering development, directed towards establishment of sodium cooled Fast Breeder Reactors [FBR] and associated closed fuel cycle in India. The success of fast reactor program primarily hinges on synergism between engineering design, manufacturing technology and quality assurance. Preservice and inservice inspection plays a crucial role in ensuring the safe and reliable performance of the plants. The Fast Breeder Test Reactor [FBTR] at Kalpakkam is completing 21 years of successful operation since its first criticality in October 1985. The Plutonium rich Uranium Carbide fuel that has been used for the first time in the world has crossed a burnup level of 154 MWD/tonne without a single pin failure in the whole core creating an international benchmark. The success of FBTR is a testimony to the maturity level of quality assurance and the robustness of NDE science and technology at IGCAR, Kalpakkam.

At IGCAR, a small NDE group was established under Baldev Raj's leadership way back in early 1980. Combining a dedicated band of multi disciplinary professionals from metallurgy, physics, engineering and instrumentation and through development and application of cutting edge technologies, this group achieved international recognition within a few years. Today, the NDE Centre at IGCAR is unique in India, combining conventional and advanced NDE under a single roof with excellent expertise in the areas of modelling, research, NDE hardware and software design, development and applications. It is a Centre for Excellence and well recognised internationally. This is reflected in the over 500 publications in peer reviewed journals, successful organization of national and international conferences, including more than 15 patents, about 20 books and the international linkages and collaborations. The robust NDE technologies and methodologies developed by this group has been utilised by the strategic and core sectors in India and internationally to solve many challenging problems. This paper provides a brief overview of the quantitative NDE methods developed at IGCAR and their successful applications. The paper also highlights spin-off applications of the methods developed to other core industries as well as healthcare.

2.0 Quantitative NDE in Manufacturing Technology

2.1 Comprehensive Assessment of Steam Generator

Compared to conventional pressurized heavy water or light water reactors, a fast reactor uses sodium as the coolant. In the steam generator (SG) of Prototype Fast Breeder Reactor (PFBR) of 500 MW(e), the transfer of heat from secondary sodium to water generates steam. Since the sodium-water reaction is exothermic and generates high pressure and hydrogen, the integrity of weld joints separating sodium and water/steam and the overall integrity of steam generator is of paramount importance. Thus, the tubes and the welds have to be inspected thoroughly. PFBR has eight SGs. Quality Assurance (QA)of the steam generator starts from the raw material for the tubes and tubesheet. As part of technology development program, at IGCAR, an elaborate set of procedures have been developed for the successful QA of SG. Given below are three typical areas where extensive R & D had been done to develop reliable NDE hardware and procedure for quantitative inspection.

2.1.1 D.C Saturation Method Based Eddy Current Inspection of Tubes

The tubes to be used for the SG are modified 9 Cr-1Mo. Conventionally eddy current testing is widely used for tube inspection. However, in the present case, since the material is ferromagnetic, inspection of such materials by conventional eddy current is not feasible due to excessive noise produced by the variations in magnetic permeability caused by localised variations of stresses and composition. Hence D.C saturation method, coupled with an integrated encircling coil was specifically developed for the inspection of such SG tubes. A number of studies and experiments were undertaken to optimize the coil and the excitation frequency for best performance. Suppression of the permeability variations has resulted in improved signal to noise ratio by a factor of 5.

2.1.2 Microfocal Radiography of Tube to Tube Sheet Welds

As indicated above, the tube to tubesheet (TTS) welds are the most crucial joints as they separate water and sodium. Typical configurations of the tube-to-tubesheet welds in conventional heat exchangers involve a fillet weld to the face side (Fig. 1 a,b and c) and are not desirable because of the following reasons:

1. The existence of crevice between the tube and tubesheet may lead to failures by crevice corrosion and stress corrosion cracking

2. The weld configuration is not amenable for NDT inspection.

The disadvantages mentioned above are overcome by using the configuration shown in Fig. 1(D), which envisages a machined nipple from the tubesheet side to which the tube is butt- welded. This design has been considered acceptable for the FBR steam generator. The machined nipple has a length of about 30mm to which the tube (23 m long) is butt-welded. Due to restricted access from outside, the welding is carried out by pulsed TIG welding utilising a rotating electrode placed on the boreside. The challenge in the inspection of these TTS joints is that all linear indications need to be detected and micropores with a minimum diameter of 50µm need to be detected. Procedures based on microfocal radiography have been successfully developed and applied in the shop floor for the reliable detection of defects (fig. 2) and cracks [1-2] with sensitivities of the order of 32 microns. More than 700 joints have been evaluated and qualified by this procedure, to date.

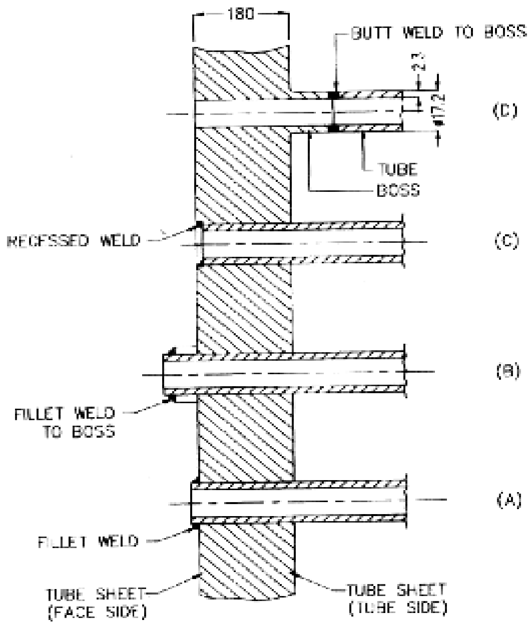


Fig. 1 Typical joint configuarations of tube to tubesheet welds

Figure 2 Concavity (arrow) and porosities (double arrow) of the order of 50 microns observed in one of a TTS weld Joint

2.1.3 Quantitative Estimation of Tube to Tube Sheet (TTS) Weld Concavity and Convexity by Replica and Videoimagecsopy

Apart from the detection of volumetric and linear defects, assessment of weld convexity/concavity is also of importance and mandatory as per the codes.

Depending on the geometry of the weld, the presence of convexity/concavity can result in concentration of stresses in and around the weld region. Under the presence of thermal, hydraulic and other pressures such regions are prone to creep-fatigue damage and have been the cause for many failures. The maximum permissible value for internal concavity is 0.2 mm and convexity is 0.35 mm as per the PFBR specifications. Measurement of internal convexity and concavity of tube to tubesheet welds poses a challenge. Due to problems of access, dial gage readings are not accurate. At IGCAR, an elegant technique has been developed using videoimagescope based on the principles of geometrical optics for determination of internal convexity and concavity with an overall accuracy of ±50 microns for concavity and ± 20 microns for convexity [3]. Replica technique based on application of silicon rubber compound has also been developed for profiling the TTS welds with an overall accuracy of 20 microns. Both these techniques have been successfully adopted in the shopfloor.

2.1.4 Application of Acoustic Emission for Evaluation of Overall Structural Integrity of Evaporator

Though not specified in the code of practice, as an R & D effort and additional confidence building measure in the evaluation of this crucial component, Acoustic Emission (AE) was carried out during hydrotesting of Evaporator at Bharat Heavy Electricals, Trichy, Tamil Nadu [4]. AE was recorded using sensors at four different locations. The results obtained from the four sensors were similar in nature and showed that significant AE signals are generated only during the first cycle of pressurisation of the tube side and shell side and AE increases with pressure. AE generated was significantly reduced during the holding periods and repressurising cycles. Increased AE during pressurizing cycles has been attributed to micro-plastic deformation of the material of the vessel. The negligible AE generated during the repressurising and hold periods indicates the structural integrity of the vessel. The leakage of water from one of the flange joints could be detected well in advance before the physical appearance of the leak, with the help of the AE signals. Subsequently it was found that the leakage was due to breaking of the gasket of the flanged joint.

2.3 NDE in Fabrication – Application of Time of Flight Diffraction and Synthetic Aperture Focussing Technique

At IGCAR, conventional NDE such as radiography, pulse echo ultrasonics, high sensitivity fluorescent liquid penetrant and magnetic particle testing and helium leak testing are routinely employed during the fabrication of various components. A recent development has been the successful application of Time of Flight Diffraction Technique (TOFD) and Synthetic Aperture Focussing Technique (SAFT).

TOFD technique is a relatively new ultrasonic imaging method which is gaining acceptance for thick walled weldments. This technique 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 when a longitudinal wave is incident on it. The main advantages of TOFD include rapid scanning of weldments especially in a single pass making this technique more efficient, faster and accurate. TOFD also enables determination of discontinuity size and depth irrespective of defect orientation. Extensive experimentation has been undertaken at the authors' lab to evaluate the application of TOFD vis a vis other conventional techniques for quantitative characterization of thick (> 15 mm) austenitic stainless steel welds. Results of experiments clearly indicate that TOFD has the advantage of faster scanning times and can be used for quantitative characterization with accuracies better than ±10% which is inline with the results obtained internationally. The confidence gained through these experimentations, has resulted in TOFD being used as reliable NDE method for thick walled weldments replacing radiography. Conventionally and internationally, TOFD has been recommended only for thickness greater than 10 mm. IGCAR has pioneered the application of TOFD for a minimum thickness of 3.0 mm successfully by combing it with immersion technique[5]. The combination has been successfully used for the detection of porosities in 3 mm thick hex scan welds of dummy fuel subassembly of fast breeder reactor (fig. 3).

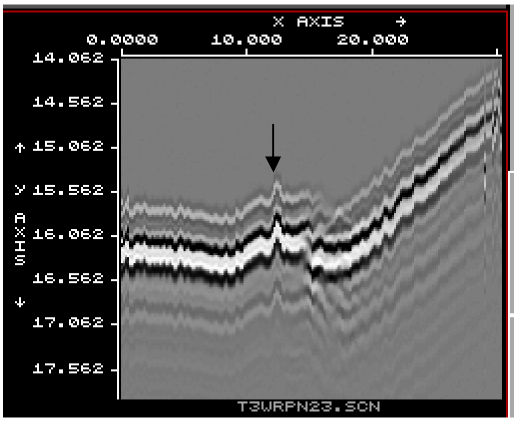


Figure 3: TOFD image of the weld specimen (3.2 mm). The porosities are indicated by an arrow.

Synthetic Aperture Focusing Technique (SAFT) is an advanced ultrasonic imaging method in which a focussed transducer is used in immersion mode. The focussed pencil beam coupled with spatial averaging of signal provides good signal to noise ratio leading to excellent lateral resolution and defect sensitivity. At the authors' lab, SAFT has been successfully employed to evaluate resistance-welded joints of fuel-clad tubes used in Pressurised Heavy Water Reactors. These fuel clad tubes had a wall thickness of 0.3 mm and the required test sensitivity of 10% of wall-thickness. The defects with this sensitivity could not be obtained by conventional immersion testing due to noise signals from tube ID surface weld upset. SAFT along with advanced signal processing methodologies such as Demodulated Auto Correlation function developed by the authors' team was successfully employed to test the end cap weld joints [6]. To set the sensitivity, a 10% ID defect was introduced in the weld upset of the end cap clad tube by careful electro discharge machining. Immersion testing was carried out using 4 MHz probe on these joints. The SAFT image obtained from a 10% deep defect in this weld is shown in Fig. 4.

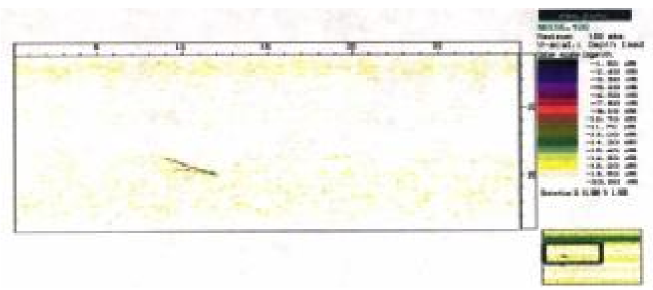
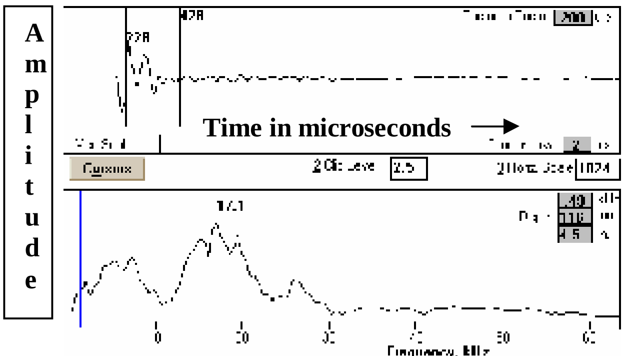


*Figure 4:*SAFT image of an end cap weld of 14.7 mm diameter tube from a 0.1 mm diameter, 0.037 mm deep (10% of wall thickness) reference defect on the

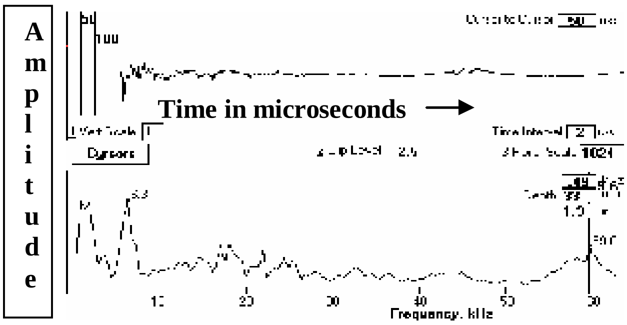
2.4 Pre-service NDE- Integrity Assessment of Concrete Structures using Impact Echo Technique

Considerable research and developmental efforts have resulted in successful application of impact-echo technique for the assessment of concrete structures. The technique was successfully adopted for integrity assessment of a ring beam of Pressurised Heavy Water Reactor (PHWR) containment. For developing the test procedures, two mock up calibration blocks were made. The block-I, with a size of 4000 x 4335 mm and representing a circumferential length equivalent to about 4 degrees of the ring beam contained simulated flaws, viz. voids of sizes 50, 100 and 200 mm at a depth of 500 mm, surface opening cracks of 25, 50 and 75 mm depth, reinforced bars of diameter 20, 32 and 45 mm at a depth of 50 mm etc. In order to study the response of the delamination of reinforced rods, various rods of diameter 20, 32 and 45 mm each at a depth of 50 mm were kept and shaken before the settling of the concrete to produce disbond at the steel-concrete interface. The results have indicated that voids of diameter 100 mm and 200 mm could be detected at the depth of 500 mm and reinforced rods of diameter 20, 32 and 45 mm could be detected at a depth of 50 mm. The depth of surface opening cracks could be measured with an accuracy of about 10%. The delamination of the rods also could be detected (fig. 5). In order to find out the depth at which the 50 mm diameter void could be detected, another test block (block-II) was made. In this block, 50 mm diameter voids were kept at various depths viz. 100 mm, 200 mm and 300 mm. The voids of 50 mm diameter located at 100 mm and 200 mm depth could be detected. However, the 50mm void at 300 mm depth could not be detected.



X-axis is time in microseconds in upper graphs and Y axis in both the graphs is amplitude

(a)



(b)

Figure 5: Response of reinforced rod (a) without and (b) with delamination – X-axis in upper graph is time in microseconds while y axis in both the graphs is amplitude.

Based on the optimized test parameters identified with the help of studies carried out on the mock up blocks, impact echo testing was successfully carried out on the actual ring beam of the reactor containment structure for assessing its structural integrity [7].

3.0 NDE for In-Service Inspection - Development of Electromagnetic Sensors and Robotic Vehicles for In-Service Inspection (ISI)

In-service Inspection (ISI) of fast reactor components is a challenge. The NDE sensors and instrumentation should be capable of withstanding the radiation environment and the temperatures present. The presence of radiation makes access also difficult. However, regulatory practices require periodic ISI to ensure the integrity and safety of a variety of components such as the main and safety vessel, steam generator etc. Robotic vehicles with special NDE sensors are the solution to this problem. Visualising this problem, a strong group has been established at the authors' Centre in the area of robotics. This group in synergism with the NDE group has successfully developed a variety of robotic crawlers and devices to which NDE sensors can be attached [8]. Two interesting case studies are presented to highlight the above mentioned synergism while a third case study highlights the importance of synergism of techniques for comprehensive ISI of cracker tubes.

3.1 ISI of Steam Generator Tubes

The importance of SG has been indicated in Section 2. ISI of the SG tubes is very important to ensure continuous availability of plant. Since the material of the SG tubes is modified 9Cr-1Mo, conventional eddy current testing used for routine ISI of tubes in plants, cannot be applied. Hence remote field eddy current (RFEC) testing technique has been developed [9]. It is to be emphasized here that the entire hardware, probes, instrumentation and methodology has been developed in-house. One of the problems likely to be encountered during the ISI was the examination of the expansion bend region. In order to negotiate the expansion bend regions, a novel flexible RFEC probe with tungsten carbide rings and cores was developed. Finite element modeling was used for optimising the excitation frequency and the spacing between the exciter and the receiver coils of the probes. This is dwelt in greater detail in section 4.1. Wavelet transform based signal processing method has been incorporated to suppress the influence of bend regions. Since sodium deposits are likely to be present on the tubes, experiments were carried out to study the influence of sodium deposits present on the outer surface of SG tubes or in the defects, on the ECT signal. A few SG tubes with OD grooves of different depths were exposed to sodium at 773K for 2 hours (setup shown in fig. 6)and then taken out after draining the sodium. RFEC measurements were carried out prior to and after sodium exposure. Visual inspection carried out after sodium exposure confirmed the presence of sodium deposits in the grooves and also on the tube outer surface. A change in the shape of RFECT signal was observed for all the defects after the exposure as shown in Fig. 7 and this was attributed to the electrical conductivity of the sodium. However, the relative amplitude of the RFECT signals was found to remain constant prior to and after the sodium exposure. Using this peak-to-peak amplitude, it was possible to detect and size defects deeper than 10% wall loss, without need for any signal processing to suppress the sodium effects.

Figure 6: Sodium test vessel used for studying the influence of sodium in defects in steam generator tubes on remote field eddy current signals.

Since the entire ISI has to be carried out in a remote manner, a compact prototype spider robot with closed loop servomotor controlled device has been developed for ISI of SGs. The robot walks over the tube sheet and positions winch controlled eddy current probe for ISI with an accuracy of ± 0.5 mm and scans the probes at a speed of 200 mm/s.

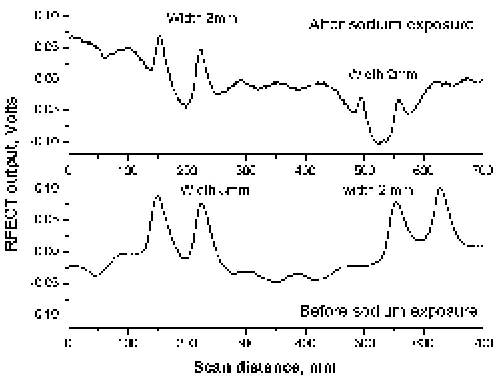


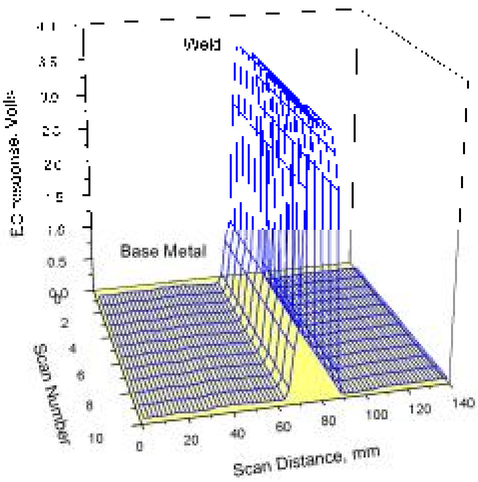
Figure 7: RFEC signals before and after exposure to sodium for a steam generator tube having 10% wall loss defects(width 2 mm and 3 mm).

3.2 ISI of Main Vessel and Safety Vessel Welds through Ultrasonic Testing and Eddy Current Imaging

The primary containment structures of pool type PFBR comprise the main vessel (MV), the safety vessel (SV), and the reactor roof structure. The main vessel and reactor covers confine the primary coolant and cover gas. The main vessel supports the primary circuit equipment and core supporting structures. The main vessel is guarded against any sodium leakage by the outer safety vessel, which is placed concentric to the main vessel. The inter-space between main vessel and safety vessel is relatively small, typically about 300mm and is at ~ after 23 K. It is required to carry out ultrasonic ISI of MV/SV welds and CCD-based visual inspection of outer and inner surface of the MV/SV.

For ultrasonic ISI of welds, precise location of weld centreline is required. For this requirement, a 423K withstanding high lift-off eddy current probe and test procedure that involves raster-scan imaging of the probe over the weld regions for centreline detection with an accuracy of $\pm$ 1 mm has been developed (Fig. 8). A four-wheel drive, remote controlled robotic inspection vehicle that carries remote inspection modules for ultrasonic, eddy current and visual inspection is developed in collaboration with Bhabha Atomic Research centre, Mumbai for ISI of MV/SV. The vehicle is designed to move around the cylindrical and curved surfaces in the interspace to facilitate inspection even in the bottom curved regions.

(a)



(b)

Figure 8: a) High temperature eddy current probe developed for location of weld centerline b) Eddy current image of weld

4.0 R & D in NDE

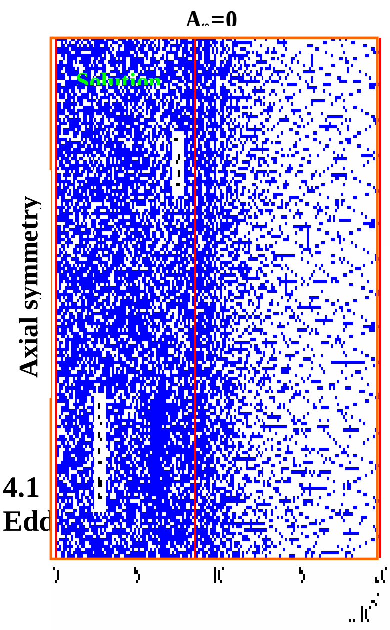
Extensive expertise has been developed in the areas of modelling and application of conventional and advanced digital signal and image processing approaches for enhanced defect detectability and sensitivity. The methodologies that have been developed have been applied successfully for enhancing radiographic images, thermographic images and UT signals. Wavelet based transforms have been successfully applied for feature extraction and classification of defects in thermographic images [10]. Artificial neural networks have been successfully applied for classification of defects detected by eddy current testing[11]. A novel application of ANN has been for prediction and classification of strain and strain rate based on IR thermography measurements during tensile deformation of AISI type 316 SS [12,13].

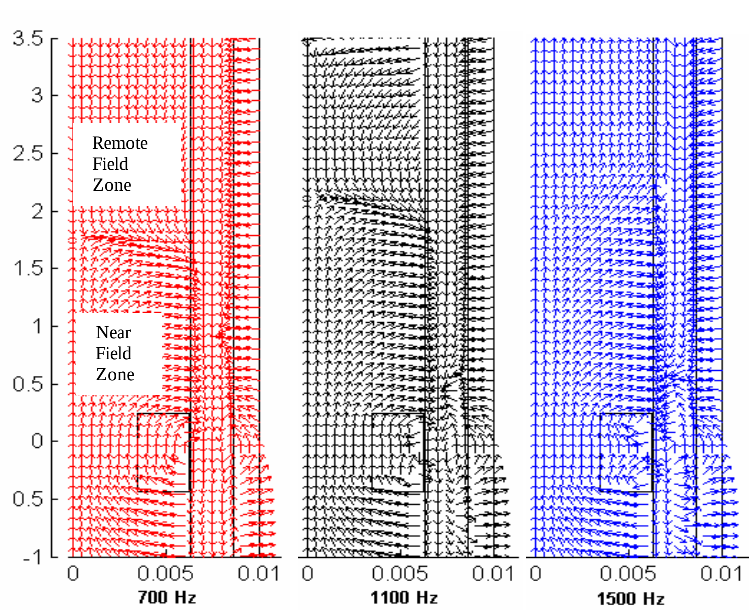
One of the pioneering applications has been utilising ultrasonic velocity measurements for microstructural characterisation. A new correlation between ultrasonic shear wave velocity and Poisson's ratio has been established for isotropic solid materials, based on the data generated experimentally and collected from the literature. Poisson's ratio has been found to decrease with increasing ultrasonic velocity in various solid materials such as metals and alloys, ceramics and glasses, intermetallics and polymers. The slope of the plot of the ultrasonic velocity against Poisson's ratio is found to be almost constant for any given alloy system with different microstructures associated with various heat treatments, alloying elements, grain size, temperature effect, etc. Further, it has been demonstrated that ultrasonic shear wave velocity is a better parameter for materials characterization as compared to longitudinal wave velocity [14]. Excellent correlation has also been established between room-temperature tensile properties and ultrasonic velocity with the microstructural changes that occur during ageing treatments in Ni-based superalloy Inconel 625. For the first time, at the authors' Centre, the influence of various precipitates, such as intermetallic phases gamma'', Ni-2(Cr, Mo) and delta, and grain-boundary carbides, on yield strength and ultrasonic velocity, has been demonstrated [15].

4.1 ... of
Edd...

Remote field eddy current (RFEC) non-destructive evaluation (NDE) technique has been chosen for in-service inspection of modified 9Cr-1Mo ferromagnetic steam generator (SG) tubes of PFBR. RFEC technique uses separate exciter and receiver coils and low excitation frequencies for NDE of tubes from tube-side. In this technique, induced voltage in a receiver coil placed at 2 to 3 tube diameters away from the exciter coil is measured. The optimum distance of the receiver is 42mm from the exciter.Reliable detection and sizing of defects in SG tubes requires that the excitation frequency is optimized and the receiver coil is positioned in remote-field zone which is at an optimum distance from the near-field zone of conventional eddy current testing. Detailed finite element analysis has been carried out to examine the electromagnetic field-defect interactions in this technique. For this purpose, an axi-symmetric model and a 3-D code have been developed in-house. Triangular and hexahedral meshes have been employed in axi-symmetric and 3-D models and remote field eddy current signals due to various defects have been predicted at different frequencies and inter-coil spacing. Typical discritised mesh and the predicted poynting vectors of electromagnetic field at different frequencies are shown in Fig. 9.

Figure 9: Descritised triangular mesh in the solution domain comprising the exciter coil and tube and poynting vector plots of vector potential showing the near-field, remote field and transition zones at 700, 1100 and 1500 Hz. Optimum frequency is, 1100 Hz. The optimum distance of the receiver is 42 mm from the exciter.





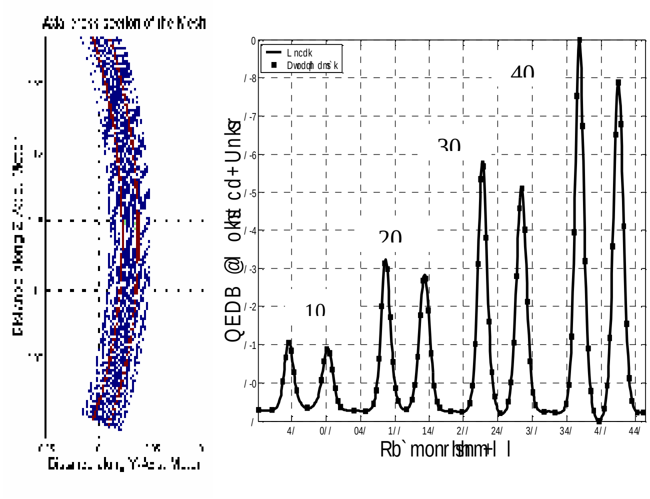


Figure 10: Typical mesh of the bend regions and the predicted RFEC signals for 10%, 20%, 30% and 40% wall loss defects in steam generator tube along with the experimental signals.

Typical hexahedral mesh of the bend region in steam generator tube and the predicted signals of various wall loss defects are shown in Fig. 10. It has been possible to optimise the test frequency, excitation current and receiver coil location and its size using the finite element models.

4.3 Intelligent Welding using NDE sensors

Automation in NDE is an area that has attracted international attention. At IGCAR, an artificial (computational) intelligence controlled welding system is being developed in a collaborative mode for on-line monitoring and control of GTAW process for welding of austenitic stainless steel and titanium alloys [17]. This system is planned as a strategic measure to enable remote repair welding of Fast Reactor Main Vessel and dissolver tank in the reprocessing laboratory. IR based NDE sensors along with visual sensors (CCD based) are incorporated in this system. Experimental studies by the authors indicate that IR thermography is an appropriate NDE method for beadwidth, joint depth and online defect detection during welding. Figure 11 shows typical isothermal patterns for two different penetration depths of 100% and 60% obtained using IR camera during GTAW of AISI 316LN SS. The computed bead widths based on the analysis of thermal images correlated well with the experimentally measured values from metallography with errors less than 10% [18].

Figure. 11: Thermal images recorded using IR camera for two different depths of penetration

5.0 Spin Off Applications

5.1 Aerospace and Defence

The robust technologies developed at IGCAR have been successfully utilized by other strategic sectors such as defence and aerospace and also process industries. Some of the challenging problems that have been solved based on the expertise generated at IGCAR include:

(i) Comprehensive NDE for evaluation of tail rotor blades of helicopters. The tail rotor blades are complex structures with a metal spar, composites and adhesively bonded structures. A combination of ultrasonics and radiography based procedures were evolved which was successfully applied for qualification of more than 50 sets of tail rotor blades.

(ii) Satellite bottle tanks are important components which are required to perform reliably in outer space. Ultrasonic and real time radiography based procedures were developed for critical quantitative assessment of defects in the Ti-6Al-4V alloy gas bottles. The results of NDE investigations was a vital input for fracture mechanics based evaluation of the flight worthiness of these satellite gas bottles.

Another important applications to the strategic sector is measurements of residual stresses in new, used (for varied number of landings), and rejuvenated landing gears (LG) of aircrafts of Indian Air Force using X-ray Diffraction technique (XRD). Landing gears used in the fighter aircrafts take entire load during landing and takeoff. Thus each landing gear has a specified technical number of landings. Initially after the completion of the recommended number of landings, the landing gears were discarded. Detailed analysis of the residual stresses on the landing gear indicated that while the stresses were compressive in a new landing gear, with the number of landings these stresses got transformed to tensile stresses. Rejuvenation of the landing gear was adopted. As shown in Fig. 12, the results clearly established the use of residual stress measurements for evaluating the extent of fatigue damage in the LGs, recommending the remaining life as well as their life extension and a procedure for qualifying the rejuvenation process.

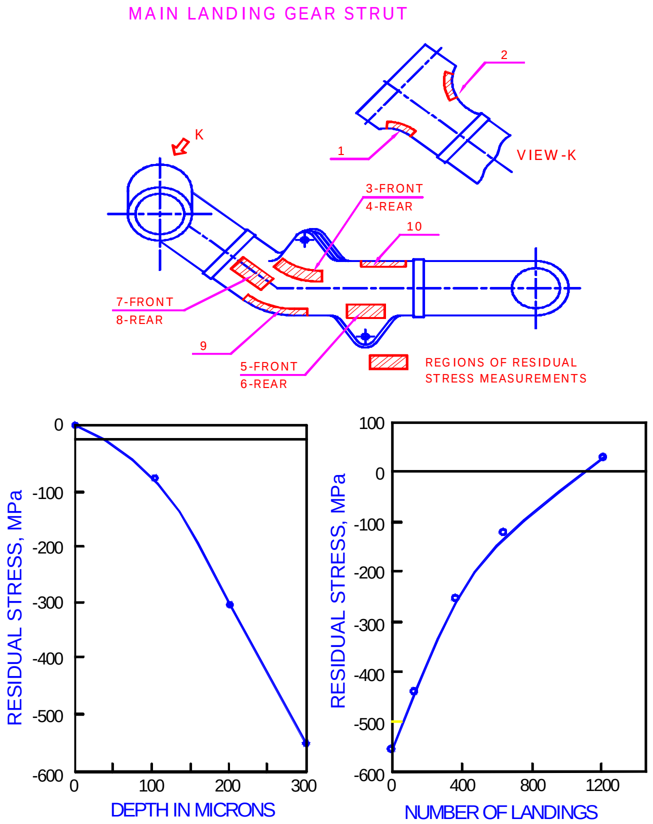


Figure 12: Stress critical regions in landing gear struts and the measured XRD data.

5.2 Infrared Thermal Imaging for Healthcare Application

It is well established that, many a time, temperature is an important precursor for monitoring the health of a component in the plant or health of a human being. In the field of healthcare, IR imaging has been internationally applied as an aid to diagnosis, but in India it is a still a grey area. In collaboration with the DAE Hospital, Kalpakkam, feasibility studies have been carried out in the areas of vascular disorders and detection of metastase of breast using infrared thermal imaging [19]. Fig 13 is the thermal image of a patient with carcinoma of breast

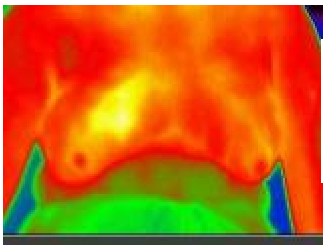


Figure13: Thermal image of a patient with carcinoma breast

5.3 NDE for Characterization of Cultural Heritage

NDE methodologies based on radiography and impact echo techniques have been successfully used for the getting an insight into the fabrication aspects of the Delhi Iron Pillar. This iron pillar made in 4th Century AD is located in the Capital city of India. Also known as the rustless wonder, extensive NDE investigations were undertaken by the authors' team to obtain an insight into mode of fabrication (casting / forging) as well as the reason for non rusting of the pillar [20].

India achieved unparallel technological excellence and aesthetic beauty in Chola and Pallva period (11th century) Bronze icons. High sensitivity radiography along with XRF and in-situ metallography has been used for characterizing and fingerprinting ancient Indian Bronzes [21]. The experience gained in the characterization of ancient bronzes was successfully utilized during the fabrication of the tallest Nataraja gifted by Department of Atomic Energy (DAE) to European Research Centre on Nuclear Sciences (CERN).

6.0 Conclusion

The work presented in this paper has been chosen from a wide spectrum research and application to highlight comprehensive expertise at the Indira Gandhi Centre for Atomic Research, Kalpakkam. It is demonstrated that success in NDE science and technology can be achieved through a multi and inter disciplinary approach. Synergism of science with technology complemented by quality personnel has been the hall mark of success for this Centre of Excellence at IGCAR.

7.0 Acknowledgement

The authors are thankful to all their colleagues in IGCAR who have contributed to the success of NDE Science and Technology.

References

1. B.Venkatraman, V.K. Sethi, T.Jayakumar and Baldev Raj, High Definition Radiography of Tube to Tube Sheet Welds of Steam Generator of Prototype Fast Breeder Reactor, Insight, 37,1995,pp-189-192.

2. B.Venkatraman, T.Saravanan, T.Jayakumar, P.Kalyanasundaram and Baldev Raj, "Assessment of weld joints of steam generator of Prototype Fast Breeder Reactor by Microfocal Radiography", Canadian Journal of NDE, Vol 25, No.4, July/Aug (2004), pp.6-13

3. V.Manhoran, B.Venkataraman, T.Jayakumar and P.Kalyanasundaram, "Quantitative Profiling of Internal Weld Contours through Videoimagescopy", Proc. 15th World Conf. on NDT (Roma 2000), Rome, Italy, 15-21,Oct 2000.

4. C.K. Mukhopadhyay, Y. Ramaseshu, B./v. Naidu, T. Jayakumar, P. Kalyanasundaram and Baldev Raj, 2005, Acoustic emission monitoring during hydrotesting of evaporator steam generator of Prototype Fast Breeder Reactor, Journal of Nondestructive Testing & Evaluation 4(1), pp. 55-64.

5. R.Subbaratnam, Baldev Raj and B.Venkatraman, TOFD and Immersion, A novel combination for examination of lower thiocknesses, Communicated to INSIGHT – European Journal of NDT.

6. P. Kalyanasundaram, C. Rajagopalan and Baldev Raj, 2004, DMAC – A versatile tool for 1-D pattern analysis for ultrasonic signals, INSIGHT, European Journal of NDT 46 (1) (2004, pp.37-43

7. Anish Kumar, Baldev Raj, P. Kalyanasundaram, T. Jayakumar and M. Thavasimuthu, 2002, Structural integrity assessment of the containment structure of a Pressurized Heavy Water Nuclear Reactor using Impact-Echo Technique, NDT & E International 35, pp. 213-220.

8. K.V. Kasiviswanathan, C. Rajagopalan, Gautam Kumar Guin and Baldev Raj, 2005, Automation and robotics for NDE applications, Journal of Nondestructive Testing & Evaluation 4(1), pp. 39-46.

9. S. Vaidyanathan, S. Thirunavukkarasu, B.P.C. Rao,T. Jayakumar, P. Kalyanasundaram and Baldev Raj, 2005, Devolopment of remote field eddy current technique for in-service inspection of ferromagnetic steam generator tubes, Journal of Nondestructive Testing & Evaluation 4(1), pp. 26-30

10. N.M. Nandhitha, N. Manoharan, B. Sheela Rani, B. Venkataraman, P. Kalyanasundaram and Baldev Raj, Advanced Image Processing Approaches For Quantitative Characterization Of Weld Defects Detected By Thermal Imaging, Proceedings of NDE 2005, NDE 2005 , Kolkata.

11. B.P.C. Rao, Baldev Raj, T. Jayakumar and P. Kalyanasundaram, 2002, An artificial neural network for online eddy current testing, Materials Evaluation 60, pp.84-88

12. C.Rajagopalan, B.Venkataraman, T.Jayakumar, P.Kalyanasundaram, Baldev Raj, "ANN a Novel Tool for Automated Evaluation of Radiographic Weld Images", Proceedings of 16th World Conference on NDT, Montreal Canada, August 2004.

13. B.Venkatraman, Infrared Imaging for Characterization of Weld Defects and

Plastic Deformation, Ph. D Thesis, University of Madras, 2004.

14. Anish Kumar, T. Jayakumar and Baldev Raj, 2000, Ultrasonic spectral analysis for microstructural characterization in austenitic and ferritic steels, Philosophical Magazine A 80(11), pp.2469-2487.

15. Anish Kumar, T. Jayakumar, Baldev Raj and K.K. Ray, 2003, Correlation between ultrasonic shear wave velocity and Poisson's ratio for isotropic solid materials, Acta Materialia 51, pp.2417-2426.

16. B.P.C. Rao, S. Thirunavukkarasu, T. Jayakuamr and Baldev Raj, IGC Annual report, 2005, pp125-125.

17. Baldev Raj and A.K. Bhaduri, 2003, Intelligent Welding of Materials, Indian Welding Journal 36(3), pp.49-58.

18. M.Menaka, M.Vasudevan, B.Venkatraman, Baldev Raj, "Estimating Bead Width and Depth of Penetration during Welding by Infrared Thermal Imaging", Insight, Vol.7 No.9, September 2005, pp 564-568.

19. Baldev Raj, M.Jayashree, M.Menaka, B.Venkatraman, "Infrared Thermography – Advanced Medical Imaging Tool for Clinical Diagnostics", Current Science Journal, Communicated.

20. Baldev Raj, P. Kalyanasundaram, T. Jayakumar, C. Babu Rao, B. Venkataraman, U. Kamachi Mudali, A. Joseph, Anish Kumar and K.V. Rajkumar, Nondestructive evaluation of Delhi Iron Pillar, Current Science 88(12) (2005) pp.1948-1956

21. Where Gods Come Alive, Baldev Raj, C.V.Sundaram and C.Rajagopalan, Published by Vigyan Prasar, New Delhi, 2000, pp. 72-95.