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Non-Destructive Examination of Bimetallic Weld Joints in Fabrication of Nuclear Equipment

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Abstract

This paper Contains non destructive examination of bimetallic weld joints made of Stainless steels cladding on low alloy steel base metal. Stringent material requirement of various components, which generally demands different component materials, necessitates need of bimetallic joints in nuclear equipment manufacturing. Development of bimetallic joints and its quality assurance procedure is overviewed in the paper. Feasibility of application of different NDE methods for examining different weld configuration (like butt weld, T weld, corner welds with constrains) is evaluated. Formulation of the non-destructive examination procedure is discussed at length. Ultrasonic examination is found best-suited method due to its higher sensitivity to planner defects and reasonable sensitivity to volumetric defects. Detection of planer defects and their repair is essential to ensure satisfactory operation of equipment as planer defects may lead to premature failure of the equipment. While evolving ultrasonic examination procedure making of reference blocks, scanning directions and reporting are given special considerations. Problems encountered in the examination and their dispositions are also covered. Flaw Characterization through discontinuity indication evaluation is also mentioned. Applications of recent developments in NDE methods for evaluating welds are also covered in this paper.

Keywords: *Bimetallic, Stainless steel (SS), Low alloy steel (LAS), Pure austenitic SS consumable, Non destructive examination (NDE), Ultrasonic examination (UT), Radiographic examination (RT), Liquid penetrant examination (LPT), Visual examination (VT), Magnetic particle examination (MPT), Side drill hole (SDH), Flat bottom hole (FBH).*

1. Introduction

Bimetallic parts are used in manufacturing of equipments to satisfy different functional requirements of material. Functional requirement of material are strength, corrosion resistance or heat resistance. Stainless steel, Ni alloys and titanium are used for corrosion resistance. Application point of view stainless steel provides good corrosion resistance in chloride free environment, Ni alloys provides better corrosion resistance (specially stress corrosion cracking) even in chloride environment due to inherent higher Ni content, Ti is the best material in the seawater environment. Base material for bimetallic is mostly steels to provide required strength. Bimetallic materials are manufactured either by fusion welding or explosion welding process. Bimetallic of stainless steel & Ni alloys can be easily manufactured by fusion welding process whereas bimetallic comprising titanium is manufactured by explosion welding due to poor weld ability of titanium. Bimetallic comprising titanium is used in manufacturing of heat exchangers. In general reference code governs the manufacturing requirements. penetration butt welds, tee welds & corner welds. These welds were examined at various stages in the process of welding to produce good quality welds.

In this paper manufacturing code followed is ASME boiler & pressure vessel code III NB. ASME Sec V provides guidelines for preparing non-destructive examination procedure.

2. Development of Bimetallic Joint

Welding between bimetallic parts and bimetallic to SS is required for manufacturing of equipment. Bimetallic material is welded after removing SS cladding up to minimum 2mm depth from SS-LAS interface at location where welding is required. This is carried out to facilitate welding of LAS to LAS. In case of SS to bimetallic welding clad material is removed and deposited using pure austenitic SS steel buffer layer and corrosion resistant SS. Clad material is removed considering followings,

- This facilitates welding between metals providing strength to the equipment.
- Acceptance criteria for clad are relaxed in comparison to welds.
- In case of lack of bond between clad and base metal, ultrasonic wave propagation may be obstructed.

Bimetallic to bimetallic welding: Pure austenitic stainless steel consumable material is used as buffer layer on LAS to provide required mechanical properties and desired chemistry of the weld metal, subsequent welding is carried out with corrosion resistant SS consumable.

Bimetallic to SS welding: Corrosion resistance SS consumable is used for welding weld deposited clad on bimetallic and SS.

3. Type of Joints Encountered

Different type of weld joints and base metal are indicated in the table –1. Sketches of the weld joints are shown in Figs. 1 to 4.

4. Examination of Bimetallic Weld Joint

Non-destructive examinations are carried out to detect discontinuities in weldment. Discontinuities in bimetallic joints may be grouped as mentioned below on the basis of their nature.

Volumetric discontinuities: Mostly occurs in the weld metal. These discontinuities are slag inclusion, pores, excess penetration & inclusions.

Planner discontinuities: Mostly occurs at interface, HAZ and adjacent parent metal: These defects are cracks, lack of bond at clad - base metal interface, lack of fusion, under-bead cracking, lack of penetration, lamellar tearing & undercuts. Lamellar tearing occurs in presence of inclusions in thick base metal with tee & corner weld joints. Cracking occurs in welds also.

Discontinuities grouped as planner are most dangerous due to short radius at ends, which cause stress concentration at ends. It may lead to brittle fracture of the material. Material fails without plastic deformation & fracture can be almost instantaneous. Because of this reason planner defects like cracks, lack of fusion, incomplete penetrations are not permissible in codes. Volumetric discontinuities have rounded ends & tolerable to some extent, however volumetric discontinuities are not tolerable in equipment with thin pressure boundary welds as volumetric discontinuities may form leak path. Detection of planer discontinuities and their repair is essential to ensure satisfactory operation of equipment as planer defects may lead to premature failure of the equipment.

Liquid penetrant examination (LPT) or magnetic particle examination (MPT) are the methods to detect surface discontinuities on face side or root side (if accessible) of weld.

Radiographic examination (RT) or ultrasonic examinations (UT) are carried out to detect internal discontinuities in the weldment. Generally either of the method is used for examining welds depending on constrains for examination, weld metal, type of weld etc.

Magnetic particle examination is not suitable to non-magnetic materials. Austenitic stainless steel is frequently used in manufacturing of nuclear equipment. Iron powder used in magnetic particle examination cause corrosion of stainless steel. Residual magnetism in magnetic material cause arc deflection during subsequent welding. Considering these aspects liquid penetrant examination is preferred examination instead of magnetic particle examination in manufacturing of nuclear equipment.

Radiographic examination is most preferred examination for butt welds. Radiographic examination is used for welds where ultrasonic examination can not be carried out in the situations mentioned below,

Ultrasonic examination of thick SS welds may be impossible due to high attenuation of ultrasonic beam associated with course grain SS weld metal. Geometric constrain may restrict ultrasonic probe movement resulting in partial scanning of weldments. Higher difference in acoustic impedance of materials in bimetallic or lack of bond between clad & base metal.

Radiographic examination has good sensitivity to detect discontinuities grouped as volumetric discontinuities, whereas it has limited sensitivity to detect discontinuities grouped as planer discontinuities at interface, HAZ and adjacent parent metal.

Discontinuities perpendicular to radiation may be missed by radiographic examination but Discontinuities perpendicular to ultrasonic beam reflects back larger amount of ultrasonic waves results in higher sensitivity for detection of these discontinuities. Ultrasonic examination has best sensitivity to detect discontinuities grouped as planer discontinuities, whereas it has limited sensitivity to detect discontinuities grouped as volumetric discontinuities. Ultrasonic examination is sensitive enough to detect under bead cracking in bimetallic joints with use of double crystal longitudinal probes. Ultrasonic examination is the best method for examining tee & corner welds, in case of radiographic examination of these welds many exposures may be required and lack of bond may not be detectable. Considering these aspects ultrasonic examination is preferred to radiographic examination while examining equipments manufactured contain bimetallic parts. Critical joints forming high-pressure boundaries should be subjected to both the examinations. Non-destructive examinations at various stages of bimetallic welding are mentioned in table 2.

5. Formulation of NDE Procedures

As explained above ultrasonic examination is preferred for examining welds containing bimetallic, therefore evolution of ultrasonic examination procedure is elaborated in comparison to radiographic & liquid penetrant examination procedures. Important features of each procedure are mentioned below.

5.1 Liquid Penetrant Examination

Surface preparation, application of dye, dwell time of dye, extra dye removal, application of developer, development time & chlorine, fluorine content are as per requirement of article 6 ASME sec V. Evaluation of indication after conducting examination was as per requirement of NB 5350 ASME Sec III NB.

5.2 Radiographic Examination

Shooting technique for each type of weld joint to be examined is prepared as per recommendations in article 2 ASME Sec V. Sensitivity requirements indicated in table NB 5111-1 ASME Sec III NB are followed instead of requirements listed in article 2. Source to film distance and type of film is decided to meet the sensitivity requirements for given X- ray generator or gamma source. Acceptance of radiographs is as per the requirements of the ASME Sec III NB 5320.

5.3 Ultrasonic Examination

Ultrasonic examination procedures prepared for evaluating the weld joints and corrosion resistant deposition on the welds as recommended in article 5 ASME Sec V. Contact manual pulse echo ultrasonic method is used for evaluating weld joint. Important aspects in ultrasonic examination are preparation of reference block, selection of probes, determination of scanning directions, acceptance standard & report preparation. Due importance should be given these aspects while preparing ultrasonic examination procedure. Other aspects like overlap during scanning, scanning speed, machine calibration check etc are standard practices suggested in article 5 and same should be followed. Acceptance of indications is as per the requirements of the NB 5330 ASME Sec III.

5.3.1 Preparation of Reference Blocks

Reference block for examination shall be made by same material specification, product form & surface finish that will be examined. Welding process, weld consumable and post weld heat treatment (if any) shall be the same that is used in production weld. Size of the reference block should be sufficient to provide enough space for machining reference reflectors of recommended size & for picking reflection from reference reflectors. Side drill holes (SDH), flat bottom holes (FBH) and notches are used as reference reflector. Ideally FBH represent planer defects, SDH represent volumetric defects and notches represent surface defects. Size of the reference reflectors is governed by ASME Sec V (T-542.2.1) for various thicknesses of welds.

When examination is conducted from cladding side then reference block should also be cladded on scanning surface. Reference block for different type of welds are shown in the Figs 5 to 9 for typical weld types shown in figure 1 to 4.

5.3.2 Examination of Corrosion Resistant Deposition on Las

5.3.2.1 Reference reflectors (as shown in fig 5)

3.2 mm FBH from LAS side up to weld and base metal interface or 3 mm SDH at interface for detecting lack of bond. 2 mm flat end SDH at deposition & base metal interface for detecting cracking in the heat affected zone.

5.3.2.2 Probe selection

Straight beam double crystal probe & longitudinal angle beam (70^{o}) duel crystal probe.

5.3.2.3 Calibration

Straight beam scanning should be calibrated with 3mm FBH & Angle beam scanning should be calibrated with 2mm flat end SDH.

5.3.2.4 Scanning

Scanning should be performed from corrosion resistant deposition side. During both straight beam & angle beam scanning probe shall be oriented parallel to weld bead axis first and then by rotated by 90^o with respect to vertical axis.

5.3.3. Examination of Welds

Location of reference reflector is decided on the basis of discontinuities expected, scanning surfaces accessible, attenuation properties & thickness of weld metal. Ultrasonic beam attenuation is high in stainless steel welds. Therefore reference blocks should be made similar to the weld joint being examined and reference reflectors shall be located in such a way that ultrasonic beam travel in weld metal is almost same during calibration & actual examination. Ultrasonic examination becomes impossible if thickness of the weld being examined is large, in such situation reference reflectors should be located such that scanning should be performed with minimum beam path in welds (i.e. ½ V path). In order to facilitate scanning welds should be designed without reinforcement so that probe movement is not obstructed by reinforcement & full weld volume and adjacent base metal can be scanned with minimum beam path in welds (i.e. ½ V path).

5.3.3.1 Reference Reflectors

3.2 mm SDH in weld metal parallel to weld axis as shown in Figs. 7 to 9. These reflector represent longitudinal discontinuities in weld metal. Square notch (1 mm deep X 3.2 mm wide X 51 mm long) in LAS base metal represent surface & planer discontinuities in HAZ.

5.3.3.2 Probe Selection

Straight and angle beam probes of suitable size and frequency should be used. Longitudinal angle beam probes are required while examining thick austenitic SS welds. Longitudinal angle beam probes should be used with calibration for half V beam path, this is due to the mode conversion of the longitudinal beam at back wall.

5.3.3.3 Calibration & Scanning

Distance amplitude curve (DAC) should be drawn by picking reflections from the reference reflectors for all the scanning except for pre-scanning & scan 5.

5.3.3.3.1 Pre-Scanning (Scan – 1)

Straight beam probes are calibrated with back wall for pre-scanning. This scanning is performed to detect lack of bond or planner discontinuities in the base metal adjacent to the weld, which may obstruct propagation of ultrasonic beams.

5.3.3.3.2 Angle Beam Scanning (Scan 2 & 3)

Angle beam probes are calibrated with respect to 3.2 mm SDH in weld to detect weld metal discontinuities. Scanning directions & calibration surface as indicated in the Figs. 7 to 9.

5.3.3.3.3 Straight Beam Scanning (Scan – 4)

Straight beam probe are calibrated with respect to 3.2 mm SDH at interface of weld buildup, weld & base metal for detecting discontinuities in buildup & at interface. Scanning direction & calibration surface as indicated in the Figs. 6 to 8.

5.3.3.3.4 Angle Beam Transverse Scanning (Scan 5)

45-degree angle beam probe are calibrated with respect to 1mm deep square notch to detect cracks in heat affected zone & surface discontinuities. Scanning direction & calibration surface as indicated in the Figs. 7 to 8. Probe is oriented at 0 to 40 degree with respect to the weld axis and scanning is performed all along the weld axis in two opposite directions.

5.3.3.4 Report Preparation

Examination details are very important for repeating the examination to reconfirm certain observations and analyzing indications. Examination reports should be formulated at the time of procedure writing and should be part of the procedure. Apart from general details (like date of examination & signature of operator, inspectors) report shall contain details that can correlate the report with specific job, weld joint, inspection stage as per process sheet. Calibration details like range calibrated, reference block used for calibration, gain settings, scanning surface & directions should also be reported for each probe. If possible a sketch may be attached depicting scanning direction from scanning surfaces. In case discontinuities indications are observed during examination location of probe with respect to some reference on weld, probe details, beam path, echo height and size of discontinuity should be reported.

6. Problems Encountered in the Examinations

Attenuation of ultrasonic beam is the major problem, one typical problem encountered is illustrated here.

During straight beam examination of weld shown in Fig. 4. SS corrosion resistance deposit on LAS was found acceptable by ultrasonic examination. SS plate was welded on the SS corrosion resistance deposit, after completion of welding weld was ultrasonically examined again. Straight beam scanning was calibrated from LAS side with respect to hole at 10mm distance from interface in Fig. 6. During scanning with this calibration many unacceptable indications observed from corrosion resistance buildup & it's interface with LAS base metal. To examine the cause of unacceptable indications corrosion resistance buildup was again examined from LAS side using reference reflectors of same size at same locations that was used in UT of SS corrosion resistance deposition, examination was found satisfactory. SDH were drilled on the calibration block at locations shown in Fig. 6. These reflectors were picked from LAS using same setup, it was observed that gain required for picking 3.2 mm SDH at buildup and final weld interface (i.e. at distance of 10 mm from interface of weld buildup LAS) was 10 db more then the gain required to pick 3.2 mm SDH at weld buildup LAS interface (i.e. at weld built up & LAS interface). It is found that 10 mm of stainless steel was producing attenuation of 10 db. Therefore, straight beam scanning after SS plate welding to bimetallic was carried out at 10 db higher gain setting. Indications that were acceptable or unnoticed in ultrasonic examination after SS corrosion resistances buildup on LAS were magnified by 3.16 times. Examination of similar welds after this was carried out by drawing DAC curve using SDH shown in Fig 6.

Geometry of the weldment is another cause of problems in ultrasonic examination. In our equipment weld joints were mostly tee & corner joints. During ultrasonic examination of these joins unacceptable indications are observed while scanning from vertical member in the weld, it was found in investigation that these indications are spurious indication coming after reflection from the back surface of horizontal member. The best way of investigating these indications is to make one to one sketch of the weld and parts being examined. Dimensions of the parts in sketch should be sufficient to contain far most position of the probe during scanning. Whenever unacceptable indication is observed probe location should be determined with respect to reference point of weldment then from the same location ultrasonic beam should be drawn on the sketch and echo reflector location shall be ascertained. Adopting this practice can eliminate many spurious indications.

7. Characterization of Ultrasonic Indications:

Characterization is the most critical and deciding activity in ultrasonic examination. Incorrect characterization can result in acceptance of weld with unacceptable defects or unnecessary repair work. Weld with unacceptable defects deteriorates quality of product whereas unnecessary repair amounts cost & delays. Therefore characterization of indications shall be performed carefully. Feedback from production shop during repair is valuable for confidence building of NDE personnel and corrective measures.

Once an indication is observed and evaluated as relevant indication then it has to be characterized. NDE personnel characterizing the indication shall know about weld geometry & welding processes used. Ultrasonic examination inputs for indication characterization are probe details, beam path distance, echo height with respect to echo from reference reflector, probe location with respect to reference location in weld & echo dynamics during scanning. Sometimes scanning from other directions is required to characterize the defect. Characterization of indication is performed by identifying probable defects and then eliminating probable defects one by one by following steps mentioned below to zero in the actual defect.

Probable discontinuities in the welds are known by welding processes used.

Location of discontinuity in weld is determined by using trigonometric calculations using probe angle, beam path, probe locations when indication is observed and weld geometry.

A discontinuity is further characterized by studying echo height and echo dynamics during scanning. Defects like cracks, lack of fusion, incomplete penetration, lack of bond, pores produce higher echo height in comparison to slag inclusion. Echoes from pores are instantaneous where as echoes from other defects are continuous.

Pores, slag inclusion produce echo while scanning from opposite direction on same surface whereas planer defects like crack, lack of fusion or incomplete penetration may not produce echo while scanning from opposite direction on same surface.

Defects at surface can be confirmed by visual examination.

8. Application of Recent Developments

Each non-destructive examination method has certain limitations and technological innovations are incorporated in non-destructive examination to overcome those limitations. Efforts are being made to make non-destructive examinations faster, more sensitive and economical. Computed radiography, phased array ultrasonic examination are the developments in field of radiographic examination & ultrasonic examination respectively. It is worth mentioning that acoustic emission monitoring can be used to detect cracks initiation or crack growth in welds during welding.

Computed radiography is recent development in field of radiography. Computed radiography utilizes flexible phosphor films for forming latent image, which is subsequently read by laser beam and recorded electronically. Later image on phosphor screen is erased with use of electromagnetic waves and screen is reusable. Computed radiography is advantageous over digital radiography as flexible film can be placed in contact with object being examined. Therefore, required geometrical unsharpness can be achieved even with constrain of limited source to film distance with available source size. Image

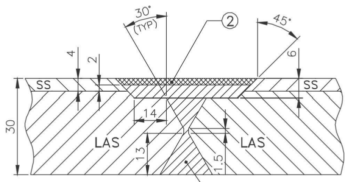

FIGURE-1

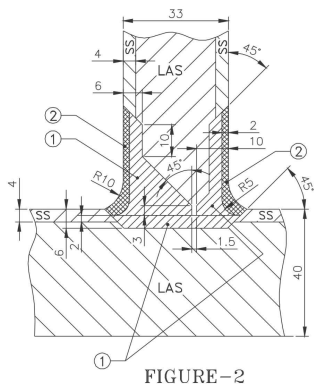

FIGURE-2

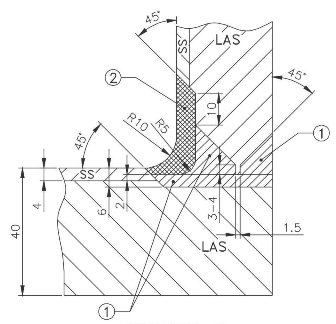

FIGURE-3

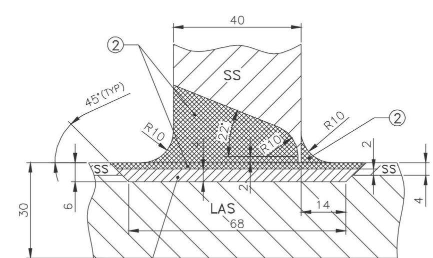

FIGURE-4

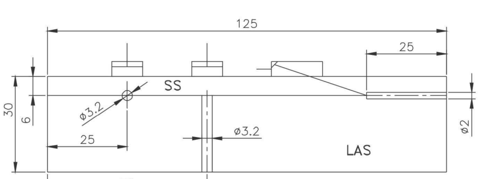

FIGURE-5

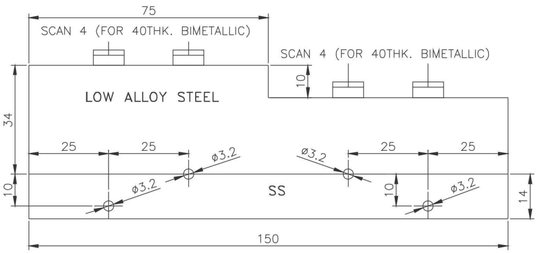

FIGURE-6

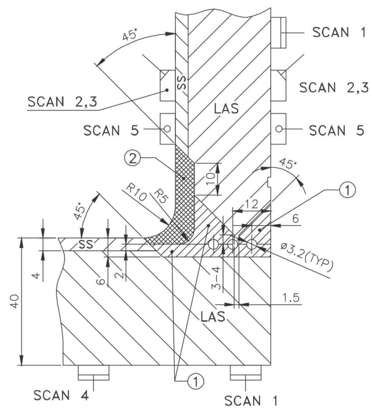

FIGURE-7

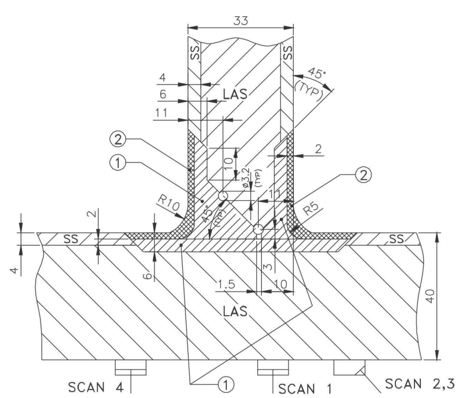

FIGURE-8

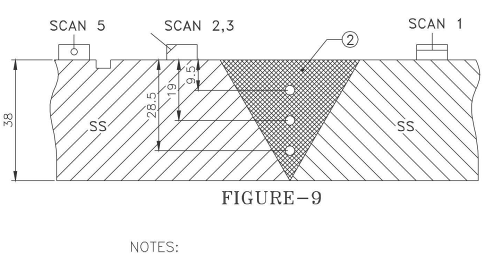

FIGURE-9

NOTES:

1. ALL DIMENSIONS ARE IN mm.
2. PURE AUSTENITIC SS CONSUMABLE IS MARKED AS (1).
2. SS CONSUMABLE IS MARKES AS (2).

Table 1:

Sr. no.	Type of weld joints	Base metals	Figures depicting weld	Figures depicting reference blocks
1.	Butt	Bimetallic to bimetallic	1	Figure -5
2.	Tee	Bimetallic to bimetallic	2	Figure – 6,7 & 8
3.	Corner	Bimetallic to bimetallic	3	Figure – 6, 7 & 8
4.	Tee	Bimetallic to SS	4	Figure – 5, 6 & 9

Table 2:

Sr. No.	Examination stage	Type of joint		
		Butt	Tee / corner bimetallic	Tee / corner bimetallic to SS
1.	Bimetallic plates before welding	UT	UT	UT
2.	After removal of cladding & weld edge preparation	Visual & LPT	Visual & LPT	Visual & LPT
3.	During deposition of cladding	Stage not applicable	Stage not applicable	UT & LPT
4.	After deposition of cladding	Stage not applicable	Stage not applicable	UT
5.	After root welding & root treatment of full penetration weld	LPT	LPT	LPT
6.	After completion of weld & deposition of cladding	LPT, UT of corrosion resistance deposit & RT of weld	UT & LPT	UT & LPT

acquired by computed radiography is digitized image that can be digitally analyzed using software.

Phased array ultrasonic is similar to conventional ultrasonic, only difference is machine and the probe. Phased array probes are array of multiple smaller piezoelectric elements arranged in specific geometry, phased array machine can activate individual or group of piezoelectric element at different orders to obtain features like electronic beam focusing, electronic beam steering & electronic scanning. Electronic beam focusing provides focusing of beam at various distance from scanning surface, focal spot of the beam can also be adjusted at different depths. Electronic beam steering provides beam angle of 0 – 80 degree for single phased array probe, therefore angle beam scanning at any angle between 0 – 80 can be performed with single phased array probe. A large portion of component can be inspected utilizing electronic scanning without mechanical movement, this allows faster inspection of large surfaces.

Electronic scanning is very useful in situations where sufficient projection distance is not available for probe movement while inspecting the welds. Inspection by using phased array ultrasonic eliminates use of multiple probes required in conventional ultrasonic. Therefore, inspections are faster.

Situations like large thickness weld joint, locations where repairs are not desirable due to cleanliness requirement of equipment, early detection of crack is advantageous. In that situations acoustic emission method can be used. Acoustic emission method monitors the acoustic activity in the weld during the welding. Acoustic activity takes place in the event of crack initiation or crack growth, which is detected and corrective measures can be taken.

9. Conclusion

Non-destructive examination during fabrication of equipment made of bimetallic containing austenitic stainless steel and low alloy steel is presented in the paper. This may be used for non-destructive examination of bimetallic containing carbon steel also as properties like density, acoustic impedance are nearly same. Amount of ultrasonic wave reflected from the interface of steels is negligible. Therefore, welds are accessible for ultrasonic scanning even from clad side also. Ultrasonic scanning may not be feasible in case of bimetallic containing titanium or nickel alloys as cladding and steel as base metal. Non-destructive examination of these bimetallic needs careful examination of acoustic properties to foresee their effect on feasibility of ultrasonic examination. In such situation ultrasonic examination may be tried after completion of welding & before deposition of clad on base metal. Radiographic examination is another alternate if ultrasonic examination is not feasible at all.

10. References

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