Automated Ultrasonic Immersion Through Transmission Imaging
Technique -A Novel Way to Evaluate Dissimilar Metal Joints

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Abstract
In a homogeneous material any source of acoustic impedance mismatch is responsible for reflection of the sound wave and for this reason, discontinuities such as voids, inclusions, lamination, porosities, large grain boundaries etc. get themselves revealed easily during pulse echo ultrasonic testing. Unlike pulse echo technique, through transmission utilizes two probes, placed opposite to each other across the material, one acting as a transmitter and the other as a receiver. In through transmission technique, the presence of discontinuity is indicated by the loss of transmitted signal. Through transmission technique is a very promising technique for the evaluation of bond between two dissimilar materials, as reflected sound wave from the interface, due to acoustical mismatch, does not come in the way of interpretation. Meticulous use of digital ultrasonic flaw detector with C scan imaging and recording facility, automated scanner with water immersion tank, probe alignment device with spherical focussed probes are some of the combinations utilized to detect lack of bond using 1.2mm diameter equivalent flat bottom hole in a joint between two dissimilar materials. Both ultrasonic testing techniques i.e., pulse echo and through transmission were used for evaluation. Results obtained were analysed and compared and it was found that problems related to interface signals, dead zone, attenuation, water column, multiple echo, reflectivity and orientation of defect are either completely eliminated or minimized in case of through transmission technique. This paper establishes through transmission technique as a strong candidate for detecting and sizing the lack of bond with great ease and high level of confidence especially in case of Electromagnetic pulse welding, Explosion welding and friction welding which are well established methods for joining two dissimilar materials. It also highlights merits and demerits of pulse echo and through transmission techniques in this context.

Keywords: Ultrasonic testing, Pulse-echo, Through transmission, Dissimilar metal bonding.

1. Introduction

A successful weld between dissimilar metals is one that possesses sufficient tensile strength and ductility i.e. it is as strong as the weaker of the two metals, and is free from cracks or any other kind of blemishes so that it will not fail during service. In case of fusion type welding process, it is important to consider various factors such as solubility, thermal expansion, melting rates, in order to determine the compatibility between two metals [1]. For strength and life prediction it is prudent to know the crack sensitivity, ductility, susceptibility to corrosion of the intermetallic compounds that are formed in the transition zone between the metals.

Variety of incompatible metals which are not mutually soluble, can be joined together by a number of the welding processes, such as explosion welding, friction welding, diffusion bonding, electromagnetic welding etc. [2]. Since minimum heat is introduced there is no melting, no heat-affected zone, and in few processes no intermetallic compounds are formed. To a larger extent it can be considered as clean joint without blemishes such as porosity, crack, inclusion which are commonly associated with fusion weld. Strength of the fusion weld depends upon the quality as well as chemistry of the deposited weld metal in a significant volume [3]. Hence, volumetric NDT methods, such as, Radiographic and Ultrasonic Testing play important roles for examining weld metal and heat affected zones. However, in case of
diffusion, explosion or friction welding NDT examination is limited to a two-dimensional plane which is interface of two dissimilar materials [4, 5].

Pulse echo (PE) technique, a most popular version of ultrasonic testing method [6], utilizes single probe which acts like a transmitter as well as receiver. Discontinuity detection in through transmission (TT) technique depends upon the loss of transmitted signal, unlike pulse echo technique which relies on the presence of reflected signal due to mismatch of acoustic impedances between discontinuity and the surrounding material. Joint between two dissimilar materials is always associated with such reflection which acts like a noise and, if large, may suppress signal from a dis-bonded area. Especially when looking for small lack of bond [6], even analysis based on phase reversal is found to be ineffective in differentiating between noise and signal.

If loss of transmitted signal due to non-uniform coupling pressure and misalignment of two probes during scanning process are taken care, through transmission technique can provide unique solution for detecting small lack of bond in the presence of very large acoustical mismatch between two dissimilar metals joined together. A probe alignment device in conjunction with an automated scanning facility [7] and immersion set up makes the scanning, operator independent. Digital ultrasonic flaw detector with B and C Scan [8] imaging facility ensures data archive and the repeatability of the results for location and size of discontinuities. Adequacy of the technique has been confirmed by analysing the results obtained for various combination such as Steel-Aluminium [9], Steel-Copper [10, 11]etc. Comparison between pulse echo and through transmission reveals that during flaw detection, latter technique can be employed for speedy scanning and reliable results provided size and accessibility do not limit the application.

2. Through Transmission versus Pulse Echo

2.1 Interface Signal

Since signals due to dis-bond and acoustical mismatch are from the same location, it is difficult to resolve them in time domain. In through transmission, only transmitted wave is received hence no interference of interface signal is observed.

2.2 Effect of thickness to be joined

In pulse echo technique thickness of metals to be joined together poses great hindrance as the multiple echoes of the metal to metal interface, in case of dis-bond, either appears before or gets superimposed, with backwall echo of the second metal. This makes interpretation rather difficult.

2.3 Water column

In pulse echo immersion UT, length of water column is to be fixed in relation to the thickness of the material being tested in order to avoid multiples of front surface (water metal interface) before first backwall echo. Such restriction does not apply to through transmission immersion UT.

2.4 Orientation and Surface condition of the defect

In pulse echo technique, sizing of defect is done either by 6 or 20 dB drop method which is governed by reflection from the flaws. If the major plane of defect is not parallel to the
scanning surface, reflected signal in case of pulse echo will be lesser in height or may not appear completely depending upon angle of inclination. However, sizing based on transmitted signal is associated with cosine error which is only 14% for angle of inclination equal to 30 degree. Similarly, poor reflectivity which depends upon the surface finish of defect may be responsible for under sizing the defect.

2.5 Attenuation

Unlike pulse echo testing in through transmission, sound wave passes through single thickness of material hence issues related to scatter and divergence is less. This enables testing of thicker and attenuating material with high reserve gain.

2.6 Ease of interpretation and flaw characterization

During the ultrasonic immersion testing of dissimilar material joint by pulse echo method many signal along with multiples from water to metal interface, metal to metal interface, backwall echo, appear simultaneously on test screen and this makes the interpretation difficult. However, these signals alone or in combination are helpful in characterizing the defects. Though through transmission is good from interpretation point of view, it does not give information about the type and depth of defect, as only one signal emerging from the opposite side of the transmitter is observed for monitoring the presence of flaws in side the material. However, as far as bond testing is concerned these limitations are of no significance since one is looking for two-dimensional planer type defect at the interface whose depth from either of the surfaces is known prior to testing.

2.7 Dead zone associated with thin section

Because of different transmitter and receiver there is no dead zone in through transmission technique but during contact testing of thin specimen low time of flight may pose some problem. Especially in immersion through transmission technique distance between two probes can be adjusted such that transmitted signal is displayed at convenient location on the screen.

2.8 Bond strength

Depending upon the quality of the bond and acoustical mismatch at interface, fraction of energy is reflected back and remaining is transmitted towards opposite face. Quality of bond is considered to be good if amplitude of the reflected signal is low and/or that of transmitted signal is high. Since pulse echo technique monitors signals from interface as well as backwall, the combination provides ample scope for carrying out qualitative analysis of bond strength varying over wide range between no bond to ideal bond.

3. Test Specimen and Experimental Set Up

3.1 Test specimen

Study has been carried out mainly on three types of bonding processes namely- explosion welding (EW), friction welding (FW) and electromagnetic pulse welding (MW). Explosion welded specimen consists of 18mm thick Copper plate welded with 28mm thick SS plate across the rectangular face with dimensions of 365x170mm. One cylindrical piece of
Aluminium (Grade 1S), 70mm diameter and 43mm thick, is friction welded to 70mm diameter and 23mm thick Stainless-Steel piece, across the flat face. Unlike above, electromagnetic pulse technique has been used for joining hollow (60mm I.D) Aluminium piece (sleeve) with (56mm diameter) solid SS piece along the cylindrical surfaces. Where ever possible, for reference level gain setting, reference reflectors in the shape of flat bottom holes having diameter in the range of 1 to 2.5mm have been made at the interface in one of the materials, representing lack of bond or dis-bonding.

3.2 Experimental set up

Experimental set up developed at CDM, BARC consists of (a) Automated scanner (b) Immersion tank (c) Digital ultrasonic flaw detector with C scan imaging and recording facility, (d) Probe alignment device and (e) Immersion probes- plain (5MHz) and focussed (10MHz).

Scanner provides three linear motions to the probe arm: X- along the length, Y- perpendicular to the X axis in horizontal plane and Z- perpendicular to both X & Y axes in vertical plane. Probe arm has provision for attaching four probe holders or probe alignment device for multiple scan. Immersion tank can hold cylindrical job having maximum diameter and length of 200mm and 3000mm respectively. Job can be rotated in clockwise and counter clockwise direction using friction rollers. All the four motions X, Y, Z & theta are encoded and each can be operated manually by switch for initial adjustment or by giving command through computer in case of programmed motions, required for automated scanning.

Set up is designed in such a way that it can perform both contact and immersion testing of jobs with different size and shape. Separate couplant unit with pump is available to ensuring uniform coupling of probe with material during contact testing.
Probe alignment device also known as variable angle fixture can be attached to the probe arm for performing immersion scanning using single probe for normal beam pulse echo technique or using two probes for pitch catch and through transmission techniques. Angle of each probe can be adjusted individually in a vertical plane from 0 to 90 degree. Similarly, distance of each probe from the central axis can be varied individually along the slotted scale to accommodate jobs of different thicknesses. For scanning the job in through transmission technique, immersion probes, one focused and other non-focused, are kept at 90 degree facing each other with perfect alignment. In an automated mode, job is scanned to and from along the length and for full coverage indexing is done either by rotating the job in case of cylindrical specimen or displacing the probe arm up or down in case of specimen having rectangular cross sections. Raw data related to A, B or C scans are acquired with probe movement in continuous or jog (step) mode. Continuous mode is useful for high speed scanning whereas jog mode is utilized for high sensitivity scanning as it allows sufficient time for signal build up necessary for being recorded. Off line data retrieval with certain software makes post processing possible even with online features.

4. Observations and Analysis of Results

Depending upon the range and gain selected, in a typical A or B scan image of pulse echo immersion technique used for evaluating dissimilar metal welding, following signals may be present: Initial Pulse (IP), First Water to Metal Interface (WIF1), First Metal to Metal Interface (MIF1) with or without multiples, First Backwall (BW), Second Metal to Metal Interface (MIF2), Second Water to Metal Interface (WIF2). However, in case of through transmission technique only two signals namely Initial Pulse (IP) and Transmitted Pulse (TP) appear on the screen and high amplitude of TP, above the threshold, qualifies the joint. In PE, low metal to metal interface signal and high backwall signal are conditions for good quality bond, hence both signals are required to be monitored simultaneously.

4.1 Friction Welding

Scanning for pulse echo technique is carried out from 40mm thick Aluminium side and range has been selected in such way that second water to Aluminium interface signal is also visible on the screen. Corresponding to a location in C scan consisting of lack of bond (LOB) at the central area and in the order of appearance following signals are present in the A and B scan displays (Fig. 3): Initial Pulse (IP), First Water to Metal Interface (WIF1), First Metal to Metal Interface (MIF1) with or without multiples, First Backwall (BW), Second Metal to Metal Interface (MIF2), Second Water to Metal Interface (WIF2). Since LOB is quite significant backwall from Steel is very weak and even second multiple of 40mm thick Aluminium is seen with noticeable amplitude.

Figure 3. Friction Weld between Al & SS, Pulse Echo Technique
C scan image for the through transmission technique (Fig. 4) clearly shows large LOB at the centre (Fig. 4a). B scan image is retrieved for a diametrical plane and A scan along this plane is generated for a good bond area away from the centre (Fig. 4b). Unlike PE, only two signals i.e. IP and TP are seen in the A scan display. Similarly, Fig. 4c and 4d represent images for poor bond and no bond areas respectively (for sake of clarity only TP is shown).

![Figure 4. Through Transmission Technique for FW between Al & SS](image)

Reference level gain is set by adjusting the amplitude of the echo obtained from 1mm diameter equivalent FBH representing LOB at the interface (Fig. 5a). Amplitude below this threshold value (50%) is not acceptable. Echo amplitude corresponding to 2mm FBH is approximately 10% FSH, (Fig. 5b).

![Figure 5. Setting of reference level gain and threshold amplitude](image)

Determination of scale factor of the C scan image and calculation of area of defect is done by using Auto CAD application software to eliminate the error, involved in UT image generation (Fig.6).

![Figure 6. Location, size and area of defect](image)
4.2 Explosion welding

While scanning with non-focused probe from Copper side, in pulse echo technique, backwall echo (from Steel) adjusted to 80% full screen height (FSH), S/N for interface echo is very low (Fig.7a) and interface echo is not observed at many points except at locations having very bad bond. Gain requirement (51.5dB) is lower than that of focused probe. However, with focussed probe while scanning from steel side S/N for interface echo is better and interface echo is distinguishable at almost all places (Fig.7b) but at higher gain (56dB). Loss of interface echo when scanned from Copper side is attributed to the large grain structure of Copper, falling in the near zone of ultrasound beam. In pulse echo technique condition of ‘lower metal interface echo with high backwall echo’ is considered as acceptance criteria for the good bond, however, in this case because of absence of interface echo only from one side, joint does not qualify as a good bond. Because of this ambiguity, pulse echo technique is not suitable for such pair of dissimilar materials. On the other hand, screen presentation for through transmission is without any ambiguity as only two well separated signals - Initial Pulse (IP) and Transmitted Pulse (TP) are present without any noise, whatsoever, at relatively low gain of 47dB (Fig.7c).

Combined images of A & B scans for pulse echo and through transmission technique are shown in Fig.8 and Fig.9 respectively. As per the colour code strip, amplitude of the signal increases from right to left; white or light red representing lowest amplitude and dark blue or black representing the highest amplitude.

Width of any B scan signal along the depth represents the width of corresponding A scan signal along time base, consisting of low amplitude components at both the extremities and high amplitude component at the centre. As compared to pulse echo, through transmission technique clearly shows (Fig.9) advantages like ease of interpretation, high S/N ratio, need for monitoring only one signal (TP), better near and far surface resolution, no ambiguity.

Figure 7. A scan images of Pulse Echo and Through Transmission Technique for Explosion Welding

Figure 8. Explosion welding PE from Copper side with non-focussed probe and reject

Figure 9. Through Transmission Explosion Welding Bad and Good bond A & B scans
4.3 Electromagnetic Pulse Welding (MW)

Unlike explosion welding, here magnetic field pressure is created to collapse 2mm thick (OD 60mm x ID 56mm x L 25mm) outer Aluminium sleeve on 56mm diameter x 25mm long SS solid mandrel to join them across the cylindrical surface. For any UT technique the biggest challenge was to obtain front surface resolution less than 2mm in Aluminium having 30mm radius of curvature. Because of curvature encountered twice in PE technique, backwall echo amplitude at good bond area is quite low (Fig.: 9a). The worst scenario exits for the poor bond area which lacks backwall echo as well as clearly resolved interface echo (Fig.: 9b). No bond area can be identified by the presence of three multiples from 2mm thick Aluminium sleeve (Fig.: 9c). Since water metal interface and first back wall echo are poorly resolved, it is difficult to decide acceptance or rejection if threshold is based on the latter.

Complicated screen display of pulse echo technique makes interpretation rather difficult in case of MW of specimen requiring high front surface resolution. This has been simplified with the use of TT which does not require either front or far surface resolution and quality of bond is judged primarily monitoring height of the TP (Fig.: 10).

5. Conclusions

Bond quality evaluation of joint between two dissimilar metals in three different configurations and joined together using three different joining processes has been carried out using automated ultrasonic immersion through transmission imaging technique. Probe alignment device has been used to minimize the misalignment between two probes. Few advantages of the technique are: (a) uniform scanning speed, coupling & contact pressure, (b) data acquisition, storage, retrieval & post processing of A, B & C scans colour images, (c) calculation of defect size and area along with its location (d) less ambiguity & ease of
interpretation, (e) high S/N ratio, (f) need for monitoring only one signal i.e. transmitted pulse. Issues such as acoustic impedance mismatch, near and far surface resolution associated with pulse echo are either completely eliminated or minimized in through transmission technique. Experimental results are quite encouraging to establish automated ultrasonic immersion through transmission imaging technique as a potential candidate for detecting flaws, as a go-no go basis for jobs with regular shape and having access to both sides.

6. Future Actions

All samples are being analysed by height of signals in time domain. Further plan is to analyse the pattern of frequency response of obtained signal with respect to quality of bond, so that response from pulse-echo and through transmission technique can be compared. Also, multi-channel facility of a digital flaw detector will be exploited to scan the job simultaneously in both the modes i.e. PE and TT making them complimentary to each other.

References