Comparative Study of Diverse Techniques for Flaw Segmentation in TOFD Images of Austenitic Stainless Steel Weld

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Abstract

Background/Objectives: Grain structure of Austenitic Stainless Steel (ASS) weld causes difficulty in defect detection while inspecting using Time of Flight Diffraction (TOFD) method. This study aims at comparing segmentation methods to overcome this difficulty based on defect characterization. Methods/Statistical Analysis: This study makes use of TOFD and Radiographic images of ASS weld pads fabricated with defined linear and volumetric defects. The Region-Based Level Set algorithm and Discontinuity Based Segmentation algorithm were explored for achieving flaw segmentation and quantitative characterization and validation of the result with that of standard radiographic results. Findings: The efficiency of the algorithms was analyzed by comparing and validating the size of defect with that of standard radiographic results in the form of error percentage. The consistency of error percentage in defect sizing (up to 11%) achieved by Region-Based Level Set algorithm for all the test images given in the database indicate that, this algorithm is the best as compared to Discontinuity Based Segmentation algorithm (error percentage up to 47%) for defect segmentation and characterization in TOFD images. Application/Improvements: The segmentation algorithm enables automation of measurement process and enhanced detection and characterization of defects at the initial stage. Further, it reduces human fatigue caused by operator while defect detection as the volume of data increases. The future direction is to fully automate the system in order to save time for interpretation and to modify the algorithm to segment images with multiple defects.

Keywords: Defect Characterization, Discontinuity Based Segmentation, Flaw Segmentation, Region-Based Level Set Segmentation, Time of Flight Diffraction (TOFD), Weld Defect

1. Introduction

Ultrasonic and radiographic testing are the oldest non-destructive testing techniques conventionally used for inspection of weldments in industries to ensure safety. B. Karthikeyan et al. indicated that wormholes, inclusion, lack of fusion, porosity, incomplete penetrations, slag line and cracks are the flaws that occur generally in weldments1. Mild steel is the most common metal used nearly in industrial and domestic purposes2. Whereas Austenitic Stainless Steel (ASS), which has high strength and creep resistance even at elevated temperature is used in power plant and most of the process industries3. Ultrasonic Testing (UT) with the advantages of single sided access, greater probability of detection for linear defects over radiographic technique is used during in-service inspection. Time of Flight Diffraction (TOFD) developed by M G Silk is an advanced ultrasonic test technique that is based on measurement of the time of flight of the ultrasonic waves diffracted from the tips of defects as shown in Figure 1 and has been widely used for inspection in industries3,4. Subbaratnam.R, et al., indicated that TOFD has the advantage of faster scanning times, high probability of detection of linear flaws like cracks, etc5. Although it is used regularly for inspection of ASS, defect detection and characterization requires

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Review of literature of Subbaratnam. R. et al., Yuwen Cao et al., Chi Dazhao et al., reveals that defective regions in the TOFD images are not very distinct as the peak of the diffracted wave is far less than the back wall echo. This causes difficulty in defect interpretation and evaluation. Hence, Yuwen Cao et al., Chi Dazhao et.al., combined TOFD data with new methods of enhancement have been attempted in the recent years to suit diverse applications. Chi Dazhao et al., have pointed out the usage of effective algorithms such as Synthetic aperture focusing technique for rapid and accurate measurement of crack tip, image enhancement and energy distribution function for crack tip recognition and weld defect detection were experimented by Yuwen Cao et al., and Chi Dazhao et al., where as Gang Tie et al., identified the arrival time approach based on cross correlation for accurate crack size assessment and image calibration through cross correlation, denoising using Weiner filter and edge detection for accurate defect recognition improves sensitivity and enhanced image evaluation.

In this work, the D-scan images are preprocessed and the defect segmentation is achieved by author on application of Discontinuity Based Segmentation and Region-Based Level Set Segmentation algorithms. From the segmented image the major axis length, a quantitative measurement was obtained. The results of both these methods are validated with bench mark value given by radiography a proven NDE method considered as a gold standard for detect detection especially for volumetric defects. Region-Based Level Set algorithm has been observed to be the best.

2. Theoretical Background

2.1 TOFD Basics and Generation of D-Scan Images

TOFD relies on the detection of the forward scattered/ diffracted ultrasonic energies from the flaws by Huygen's principle. Figure 1 indicates the principle and visualization of defects in TOFD. The scanner (Transmitter and receiver probes with encoder) are moved in the direction of arrow along the length of weld axis as given in Figure 1(b). At each step the A-Scan signals is acquired and is stacked to form the D-Scan image as given in Figure 1(c).
and 1(d) respectively. The lateral wave and the back wall reflections will be received in normal region. But when a defect occurs (Figure 1(a)) diffracted waves (2 and 2’) will be generated from the flaw tips in addition to the lateral wave and the back wall echo as given in 1(c). This is developed as a pixel amplitude change in the D-Scan image.

2.2 Active Contours Model

Michael Kass et al., developed active contour models, or snakes, defined by an energy function resulted from their work\textsuperscript{11}. They have applied active contours to various problems, like image segmentation, feature extraction and image registration. The active contour method of segmentation has found its application in the medical field\textsuperscript{12}. Michael Kass et al., R. Loganathan and Dr. Y. S. Kumaraswamy made out how a snake is a parametric curve which tries to move into a position where its energy is minimized when it coincides with segmented object boundary\textsuperscript{11,12}. The energy function is the weighted combination of internal and external forces as given in equation (1).

\[ E_{\text{snake}} = E_{\text{int}} + E_{\text{ext}} \]  

\textit{Internal Energy} (E_{\text{int}}) depends on the intrinsic properties of the curve and is the sum of elastic energy and bending energy.

\textit{External Energy} (E_{\text{ext}}) of the contour is derived from the image and is the sum of image forces and external constraint forces.

2.3 Chan-Vese Model

The Local Chan-Vese model developed by T. F. Chan and L. A. Vese, is the region-based level set method\textsuperscript{13}. It incorporates region-based information into the energy functional on local statistics to stabilize the curve evolution to local variations, instead of the gradient which appears not efficient, particularly on low-contrast object to stabilize the evolution to local variations. The functional energy is based on three terms: the global term, which includes global properties as the intensity average, the local term which incorporates local statistical information to improve the segmentation process, and the regularization term, used to ensure curve evolution stability. The additional advantage which occurs in its low sensitivity to the initialization of the curve is presented by Fouzia Boutaouche et al.,\textsuperscript{14}. The CV model basically introduces ‘fitting energy’ functional, which needs to be minimized during the process of segmentation.

3. Proposed Methodology

The methodology adopted has four different modules:
- Data Acquisition module.
- Preprocessing module.
- Segmentation module.
- Representation and description module.

3.1 Data Acquisition Module

Authors have generated their own defect database since there is no standard weld database available. The different stages of data acquisition,

3.1.1 Fabrication of Weld Specimen

Two Austenitic stainless steel (AISI 316L) double V butt welded joints of 25mm thickness were fabricated and used in this study. The specimens were welded by shielded metal arc welding (SMAW) process, using standard welding procedures. Each weld specimens were developed with two similar defects intentionally introduced during the welding process along the weld axis viz., one with volumetric defect (slag inclusion) and another with planar defect (lack of penetration). The ASS weld specimens are named as ASS_1 and ASS_2 respectively after the material.

3.1.2 Data Acquisition

The specimens were initially subjected to radiographic testing the results of which are considered as the bench mark value. TOFD examination was done after flushing the specimen faces, using Ultrasonic Flaw Detector model µTOFD of AEA Technology. The specimens are scanned using 45º angle probe of 4MHz frequency and at the end of inspection, the individual images from the database were visualized and the defects were manually interpreted. The Region of Interest (ROI), between the Lateral wave and Back wall echo were extracted from the individual images and the resulted images form the required database for this work. The TOFD images of ASS_1 and ASS_2 are given by TASS_1 and TASS_2 respectively and are shown in the Figure 2(a) and 2(e) and the radiographs corresponding to them are RASS_1 and RASS_2 and is given as Figure 2(b) and 2(f).
3.2 Image Preprocessing

In order to improve the image quality and to ease further processing, digital images acquired need to be preprocessed. The processing of these images were performed using MATLAB image processing tool. The next three modules of the methodology are implemented after dividing the TASS_1 and TASS_2 into two equal halves in order to attain image with single defect for further processing. TASS_1 is divided into TASS_11 and TASS_12 and TASS_2 is divided into TASS_21 and TASS_22 respectively and is given in Figure 2(c), 2(d), 2(g), 2(h). Chi Dazhao et.al., have discussed on the computational complexity of processing the acquired images that are in color domain. Hence the images are converted to gray scale image. Further enhancement of these images is done by performing histogram equalization, which is a contrast enhancement technique that tries to spread out the gray levels in the image.

3.3 Segmentation Module

Image segmentation is a mid-level image processing technique which is used to analyze the image and can be defined as a processing technique used to differentiate the object of interest from background in an image and to get more information in the region of interest in an image.

3.3.1 Implementation of Discontinuity Based Segmentation Algorithm

In this work, the edge detection of the TOFD is performed by application of gray level Thresholding as applied by N. M. Nandhitha et al.15 After the edge detection is completed the post processing process is done on the edge detected images in order to remove the undesirable regions. The post processing part includes the dilation, region growing (filling) and erosion. The gap between the edge pixels on the edge detected images are bridged using dilation. Region growing adds additional white pixels to differentiate the object of interest from the background. Finally erosion erodes the excess values from the region filled image to isolate the flaw or the region of interest.

3.3.2 Implementation of Region-Based Level Set Segmentation Algorithm

In this work, local statistics of the region are computed for every point along the evolving curve. Computation is separated into two stages: Initialization and updating.

The process of local region based segmentation method is initialized by selecting a mask to form the narrow band/contour. The energy is formulated by computing local mean of the region around the contour so as to achieve localization. The step of updating occur...
whenever any initialized pixel is moved from interior to exterior or exterior to interior as the contour crosses it. The statistical models of all the pixels that lie within the neighborhood of the contour are calculated. The values of force from image information and curvature penalty are updated so as to find the gradient descent to minimize energy. As the energy formulation is done by local mean, each and every pixel must maintain the number of pixel and the summation of pixel intensities both inside and outside regions of the curve. Updating of these values means transferring of values either from outside group to inside group or vice versa. New contour is updated and above procedures are repeated till the maximum iteration is attained. The global segmentation is applied on the final contour.

The number of iterations and the smoothness factors are fixed after multiple trials to achieve effective segmentation with minimal computation time for these images are as follows.

- Number of iterations: 300.
- Smoothness factor: 0.08 (The evolving curve is dynamic / rigid as the smoothness value is smaller / larger respectively. In our case a smaller value is chosen).

The results for different TOFD images were achieved in the same fashion. The size of the defect in each individual case are calculated and tabulated.

### 3.4 Representations and Description Module

Once the flaw is obtained by the segmentation algorithm it needs to be represented and described during the process of interpretation. This work focuses only on the length of the defect along the weld axis. The major axis length is the external descriptor that is used for quantitative characterization of defect.

### 4. Results and Discussion

#### 4.1 Experimental Results

The segmentation algorithm has been applied on four real-time TOFD images of ASS weld specimens with planar and volumetric defects. Sample set is given in the Figure 3(a) and 3(b). In this work both the segmentation algorithms have been applied on all the four images given in Figure 2(c), 2(d), 2(g) and 2(h).

When the discontinuity based detection algorithm is applied on volumetric flaw (Slag inclusion) image TASS_11, the intermediate result on the application of Thresholding based edge detection is a binary image which included disturbances with flaws. The application of post processing steps resulted in the final segmented image of the flaw. Figure 3(a), 3(c), 3(d) and 3(e) shows the input image, enhanced image, intermediate result and the output images. Figure 3(b), 3(i), 3(j) and 3(k) shows...
the input image, enhanced image, intermediate result and the output images when the same algorithm is applied on planner flaw (lack of penetration) image.

In case of the region based level set algorithm when it is applied on the volumetric and planner flaw images, the mask is selected initially which forms the initial contour, the energy minimization procedure is repeated for 300 iterations and the global segmentation is applied on the final contour and the result is the flaw segmented image. The initial mask, final contour and the final segmented image after the application of global segmentation algorithm are given in Figure 3(f), 3(g) and 3(h) and 3(l), 3(m) & 3(n) for volumetric and planner flaw respectively.

Once the flaw is segmented from the image background by the discontinuity based segmentation and region based level-set segmentation algorithm the major axis length of the defect in the direction of weld axis is calculated and the quantitative characterization of defects are tabulated in Table 1. The bench mark values of defect length attained from radiographs are also tabulated in Table 1.

### 4.2 Evaluation of Segmentation Results

In order to evaluate the quality of segmentation, the length of defect in the direction of weld axis is considered as the result of interest in this research.

The error of the calculated length of the defect by the explored algorithms as compared to the bench mark values are tabulated in Table 2. The equation for calculating the percentage error is given by the equation (2).

$$\text{Percentage Error} = \left( \frac{\text{Actual Value} - \text{True Value}}{\text{Actual Value}} \right) \times 100$$  \hspace{1cm} (2)

Where

- \( \text{Value}_{AC} \) – Actual value of defect 
  (The size of the defect from Radiography which is considered as reference/bench mark value).
- \( \text{Value}_{T} \) – True value of defect 
  (The size of the defect based on the major axis length at the end of application of the segmentation process).

It is evident from the Table 2 that the result of discontinuity based segmentation algorithm is not consistent and the result of the region based level set algorithm is very much consistent. In case of discontinuity based segmentation algorithm the result is not consistent because it depends purely on the image quality and on the structural element considered. However in case of region based level set algorithm though the initial mask needs to be selected, the energy minimizing procedure works well to achieve a segmented image for input which have different image quality. However the limitation in this is it depends on the initial contour selected.

### Table 1. Quantitative characterization of defects (all dimensions in mm)

| Weld Specimen | TASS_11 | TASS_12 | TASS_21 | TASS_22 |
|---------------|---------|---------|---------|---------|
| Type of defect | Volumetric Flaw | Planner Flaw |
|               | Slag Inclusion | Slag Inclusion | Lack of Penetration | Lack of Penetration |
| Radiographic result (Bench mark value) | 37.80 | 36.01 | 35.35 | 34.24 |
| Discontinuity based detection | 20.14 | 37.40 | 29.52 | 32.28 |
| Region based level set detection | 40.75 | 39.32 | 39.20 | 35.97 |

### Table 2. Defect validation (Unit is %)

| Weld Specimen | TASS_11 | TASS_12 | TASS_21 | TASS_22 |
|---------------|---------|---------|---------|---------|
| Type of defect | Volumetric Flaw | Planner Flaw |
|               | Slag Inclusion | Slag Inclusion | Lack of Penetration | Lack of Penetration |
| Percentage Error of Discontinuity based detection | 46.73 | -3.85 | 16.50 | 5.72 |
| Percentage Error of Region based level set detection | -7.81 | -9.18 | -10.89 | -5.06 |
5. Conclusion

In this research a comprehensive comparison of the discontinuity based algorithm and region based level-set algorithm for segmentation of defects in TOFD images is presented. The algorithms segment the defects and effectively quantify the defect length. The results have been validated with that of radiographic results and the best method was identified based on the error percentage attained during defect quantification. In case of region based level-set algorithm the error percentage was less than 10% when verified for four different TOFD images. The obtained results will be of much use when the inspection volume increases as it reduces error due to human fatigue. The future direction is to fully automate the system in order to save time for interpretation and to modify the algorithm to segment images with multiple defects.

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