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Real-time automatic detection of weld defects in steel pipe

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Abstract

In order to detect weld defects in steel tube, a real-time imaging and detecting system is setup. In the extracted weld seam, based on spatial characteristics near defects—variance and contrast, defects such as slags, blowholes and incomplete penetration are automatically detected using the method of fuzzy pattern recognition, and the system will automatically alarm if the defect exceeds the national standard. Compared with other methods, it is simple and fast, and has fewer misinterpretations. It can detect weld defects in real-time.

Keywords: X-ray non-destructive detection; Weld defects; Automatic detection; Fuzzy algorithm

1. Introduction

X-ray imaging is a widely used technique for inspection of industrial pieces and for the medical diagnosis of human diseases. Traditional radiographic testing with film is an expensive and time-consuming technique. Therefore, digital radioscopy that permits real-time inspection has been developed and applied. Now, experienced workers are required to evaluate the moving weld seam based on the video displayed on monitor. The manual interpretation process can be subjective, inconsistent, and easily cause fatigue. Therefore, it is imperative to develop an automatic computer-aided system to increase the objectivity, consistency and efficiency of defect inspection. In our view, automatic detection of defects in real-time digital RT system consists of two aspects: (1) identifying the defects in the weld (2) classifying different types of welding defects. When weld seam is moving, weld defects are very thin and do not have a high contrast under X-rays. Defects inspection at this condition is a very challenging problem. To the best of our knowledge, no commercially real-time automatic RT system exists today. On-line inspection requires a computationally fast and effective method, therefore the main task is now focused on the identifying and locating flaws in the moving weld. Classifying is not possible due to computational cost and time-consumption. In the process of locating and detecting defects, we always fall into the dilemma between locating all the true defects and avoiding any false alarms.

Much work devoted to the defects detection in X-ray films will be helpful to real-time defect inspection. It has already obtained many achievements with the aid of digital image processing technology, through eliminating background technique [1–4], edge detecting techniques [5,6], enhancement technique [7,8], and fuzzy pattern detection method [9]. In Ref. [8], background subtraction and histogram thresholding were implemented to separate defects from the background. Because of uneven background and noise, the obtained image may include a lot of small background region and noise besides true flaws, this will results in false alarms. Edge detecting techniques [5,6] are found to be effective only when there is a distinct contrast. Attempting to detect edges of small low contrast defects makes the method sensitive to noise. In Ref. [8], all the round defects were enhanced by measuring a similarity degree between the image and matched filter. The drawback is, however, that the enhancement is limited to defects greater than the filter, which is a strong limitation for small defects. In Ref. [9], the method tried to imitate the way a human inspector inspects radiographs and the whole image is processed. For application of above methods to fast real-time automatic detection, the methods must be improved to overcome unacceptable false alarm rates and impractical computational time. As a continuation of our research in this

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area, we restrict ourselves to the objective of this work as follows: (1) We set up a X-ray real-time imaging and detecting system. It is used for inspecting welding defects of a spiral steel pipe when it is moving along the inspection line. To speed up inspection, the moving speed is not allowed to go lower than 3 m/min. (2) The dynamic sensitivity should be higher than 4%. (3) The performance is equal to the evaluation of a human operator. Firstly, weld seam is extracted in order to reduce the computational cost, and then defects are identified and located automatically in the weld seam by employing a region detection algorithm based on image spatial characteristics (Gray level contrast between the defects and welding seam background, and gray level change degree within the defects). It can also calculate the defects' size and judge whether the accumulated size of defects exceeds the minimum standard. If the defect exceeds the minimum standard, the system will automatically alarm, sending out the marking signal at the position where the defects appear to help the workers to repair them.

2. Component structure of the system

The system consists of conversion part, processing part and serial communication part as shown in Fig. 1. The conversion part consists of X-ray source, weld seam, transmission vehicle, intensifier and CCD camera. The function of this part is to make the conversion from X-ray to visible light. Firstly, X-ray is transferred into visual light through light intensifier. Then the CCD camera transfers the light signal into electric signal and sends it to the processing part. The processing part consists of monitor, image grabber, computer, and computer screen. In this part, the electric signal is sampled and transformed into digital signal by image grabber, and at the same time it is also displayed on the monitor. The digital image is sent into the computer and will be detected using the defect detection algorithm based on fuzzy recognition theory. The result will be displayed on computer screen in real-time and stored in computer for future check or test. The serial communication part consists of Single Chip Micyoco (SCM), rotary coder, serial communication (Max232 chip), optical isolator (ADAM-4520) module and transmission device, etc. The function of this part is to obtain and transmit the information of position. The system transforms the displaced signal into the pulse signal utilizing the rotary coder and attains displacement by computing the number of the pulse. Then the displacement signal is transmitted to the computer for the defects location through serial communication.

3. Principle of automatic detection

In this part, we will introduce the principle of the detection in detail. The defects detection includes two main procedures: image preprocessing and realization of the algorithm. The detailed explanations are as follows.

3.1. Extraction of the weld seam

Usually, an automatic welding process yields a relatively uniform weld. Since only the items within a weld are of interest for the purpose of image processing, we extracted the weld area free of background. A typical X-ray image of weld is shown in Fig. 2(a). We have the prior information about brightness distribution in the points of object and background. There are three main areas in the weld image, the base metal area, the weld area, and lead plate area. The weld seam is oriented along the horizontal direction

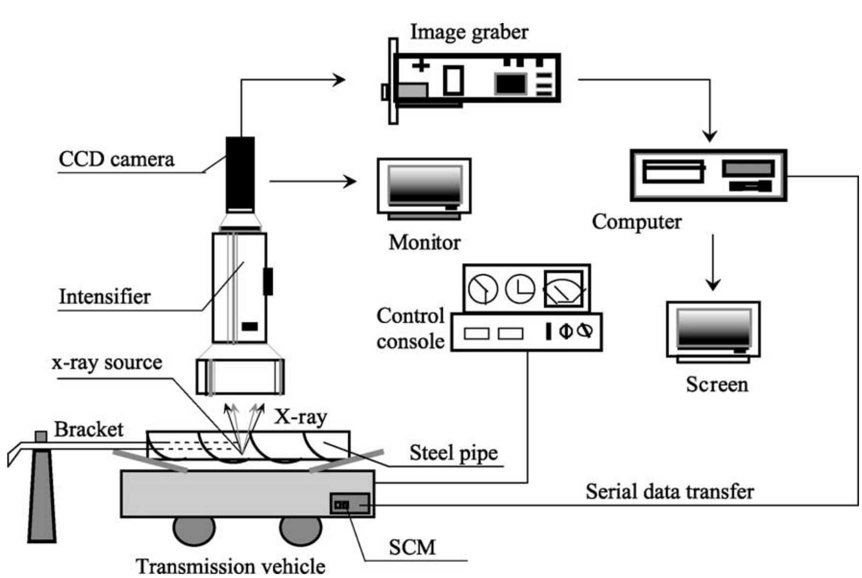

Fig. 1. Component structure of the system.

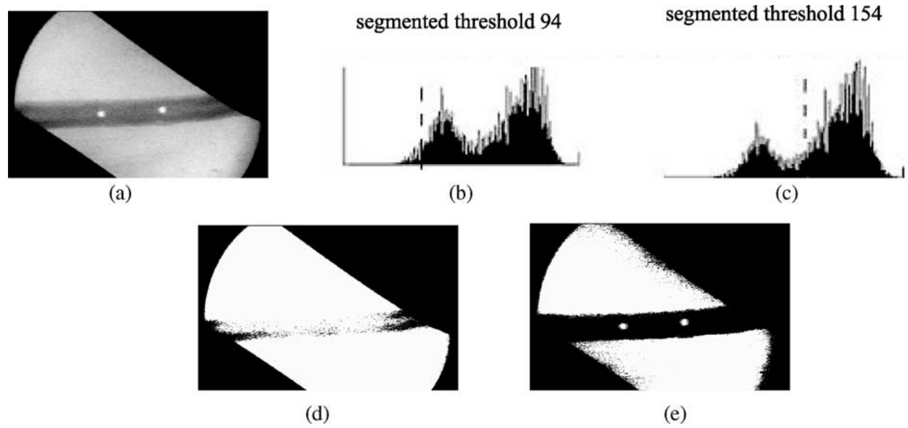

Fig. 2. (a) Original image (b) histogram with dark background and adapted threshold (c) histogram without dark background and adapted threshold (d) the result of (b) and (e) the result of (c).

and appears in the image as a darker area. Defects appear brighter as typical weld defects are lack of matter, like porosities or lack of penetration. Base metal appears brighter than both the weld seam and the lead plate area. The lead plate area is the darkest place in the image, the pixel gray level of which is nearly to zero. Since the image is continually changing with time duo to the noise and component structure, the threshold for binary image is not only automatically computed from the gray-level histogram of the image, but also adaptively changed with image's changes. The results are not ideal because there are three areas in the weld image. Since the lead plate is nearly dark, we first delete the lead plate area according to its low gray-level. Then the thresholding is applied to the other two left areas. To improve the detection speed, the method is adopted using adaptive segmentation algorithm to choose threshold for extracting weld seam area. The principle of adaptive segmentation is that the image is divided into two classes; the variance in the class is the least one while out of class is the biggest one. The formula is as follow

$$\mathrm{Max}\left\{\sigma_\beta(k) = \frac{[\mu_T\omega(k) - \mu(k)]^2}{\omega(k)[1-\omega(k)]}\right\} \tag{1}$$

where

$$\mu_T = \sum_{i=0}^{255} ih(i)\ \mu(k) = \sum_{i=0}^{k} ih(i)\ \omega(k) = \sum_{i=0}^{k} h(i)$$

$$k = 0, 1, \ldots, 255$$

i represents the gray level and $h(i)$ represents the distribution of gray level. This method can follow the welding seams rolling up and down on screen effectively, and guarantee defect detection algorithm used in the extracted weld seam. The segmented results with and without dark background are shown as Fig. 2. As we see, the result of Fig. 2(e) is better than that of Fig. 2(d).

3.2. Principle of automatic defect detection

After welds are successfully extracted, it is then to identify the defect areas. X-ray imaging is inherently noisy because of the quantum nature of radiation, there may be only a few photons per pixel per exposure time. Large defects can be easily detected by many methods. But small defects encounter the difficulty of differentiation between true defects pixels and noisy impulses. On this condition, the performance of typical methods is not good as compared to a human operator. In order to achieve fast and precise detection, we propose a region-based approach that imitates visual inspection of the idea of which is partly from Ref. [9]. In the weld image, defects appear brighter as typical weld defects are lack of matter. A volumetric defect appears as a bright blob, while a planar defect appears as a bright line in the image. For visual inspection, contrast and variance are important because the human visual system is very sensitive to the two parameters. Under the circumstance of a fixed contrast, the smaller the variance of an area is, the more reasonable it is a defect area. To a fixed variance, the higher the contrast of an area is, the more possible is the defect presence. The contrast is usually given by the gray-level difference between the object and its neighborhoods. This is the principle of fuzzy algorithm, from which fuzzy rules applied in defect detection algorithm comes. The concrete defects detection algorithm is as follow.

In detection of blowhole and slag inclusion, the sizes of contrast and detection area are selected as 10×3 and 6×4. The contrast areas are divided into two groups, the horizontal distances between the two groups and the detect area are 5–8 and 15–18 pixels; the vertical contrast area is also divided into two groups, the distance between the two groups and the detect area respectively are 3–6 and 8–11 pixels, the sketch of detect area and contrast area is shown as Fig. 3. Although the method of detecting incomplete penetration is the same as blowhole or slag inclusion, an incomplete penetration is not like a blowhole or slag inclusion that shows a bright point, but shows a bright line.

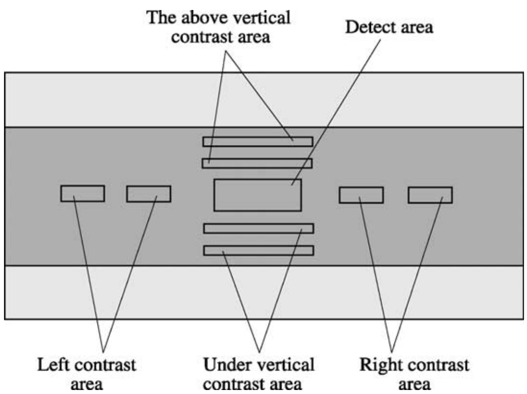

Fig. 3. The sketch of detect area and contrast area.

So in detection of lack of penetration, the detect area is selected as 2×20 pixels.

After obtaining the two groups' average gray level, we add them up and make an average to get the average gray level of the contrast area. Then we can get the average gray level difference A by subtracting the average gray level of the contrast area from that of the detected area. Thirdly a square of the difference between average gray level of detect area and the gray level value of every point in the detected area is made. At last, by adding all of obtained squares up and make an average of them we will get the variance V of the detected area.

We set the inference rules of the simplified fuzzy reasoning, as shown in Tables 1 and 2, and use it to calculate

Table 1
Inspection membership parameters of blow holes and slags

V	$A<10$	$10<A<12$	$12<A<16$	$16<A<25$	$25<A<35$	$A>35$
<376	0	2	2	3	3	3
>376 <1930	0	1	2	2	2	3
>1930 <7200	0	0	1	1	2	2
>7200 $<21,600$	0	0	0	1	1	2
$>21,600$	0	0	0	0	0	1

Table 2
Inspection membership parameters of incomplete penetration

V	$A<7$	$7<A<12$	$12<A<17$	$17<A<25$	$25<A<35$	$A>35$
<360	0	2	2	3	3	3
>360 <750	0	1	2	2	2	3
>750 <2500	0	0	1	1	2	2
>2500 $<11,600$	0	0	0	1	1	2
$>11,600$	0	0	0	0	0	1

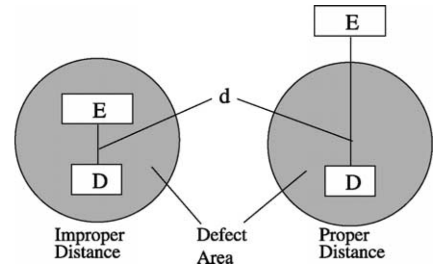

Fig. 4. The effect of distance.

the defect membership value. The values 1–3 in tables express the low, medium and high confidence. An area is considered as a part of defect if and only if the overall membership value is greater than or equal to 4. (Tables 1 and 2 are the membership value tables. Where, V represents gray value variance, A represents gray mean value difference).

In this fuzzy algorithm, another important parameter is the distance between two contrast areas: background area E and defect area D, as shown in Fig. 4, the gray round is the enlarged defect area and d is the distance. The shorter the distance is, the higher the probability is that E is overlaid with defects area D when big defect appears; on the contrary, the longer the distance is, the less relation of the two fields is. So the distance between the two compared areas should be proper, and could reflect the contrast characteristic exactly and avoid comparing the defections in the same area.

3.3. The calculation of the defect size

We need to know the size of every found defect to judge whether it exceeds the national standard or not. The procedure can be shown in Fig. 5. The black dot is a blowhole defect along horizontal direction denoted as y, where x_l is the left terminal and x_r is the right terminal of the defect. At last, the size of the defect is estimated by $((x_r-x_l)+y)/2$.

Two features were chosen to provide precision about the type of defect. One is the position, because some defects have a particular position in the weld. For example, incomplete

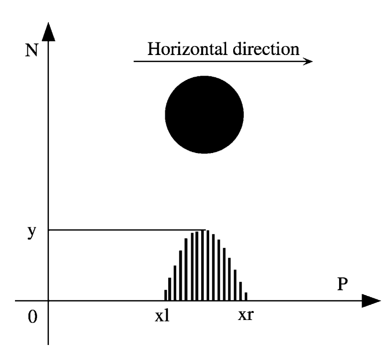

Fig. 5. Gray value accumulated sketch.

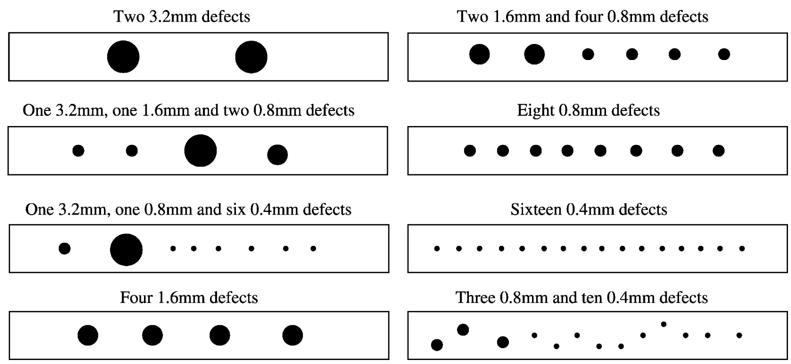

Fig. 6. The most distributed mode of rounded blowhole and slag defect.

penetration is in the middle. The other is elongation because it is the main indicator for distinguishing between planar and volumetric defects. Elongation is computed by the radio of the length to the width of the object.

3.4. The standard of judging defect

Welding seam quality should accord with GB3323 standard, and according to GB9711-88 standard: once the incomplete penetration and other flaws are found, the system must give alarm. The most distributed mode of blowhole and slag defects are shown in Fig. 6.

The figure is explained as follows:

1. The total size of the defects can not exceed 6.4 mm in the length of 152.4 mm;
2. The biggest size of defect should not exceed 2.4 mm when the thickness of the steel pipe is less than 6.4 mm.

The system will automatically alarm and send out the marking signal if the defect exceeds the standard, and mark in defect position to help the workers to repair them.

3.5. The same defect judging of consecutive frames

Because the same defect can appear in several frames, the number of defects and accumulated size of defects may be greater than existing. Therefore, it is necessary to judge whether the defects are the same one or not in consecutive frames.

Supposing the size ratio between the computer screen and real size is 1:1. If the distance between two defects on screen is equal to the displacement in consecutive frame measured by the rotary coder, the defects are regarded as the same one. Then we have to subtract one from the number of the defects and the system carries on the next judgment. We just compare the defects within three frames because the defects could not be the same at far two frames.

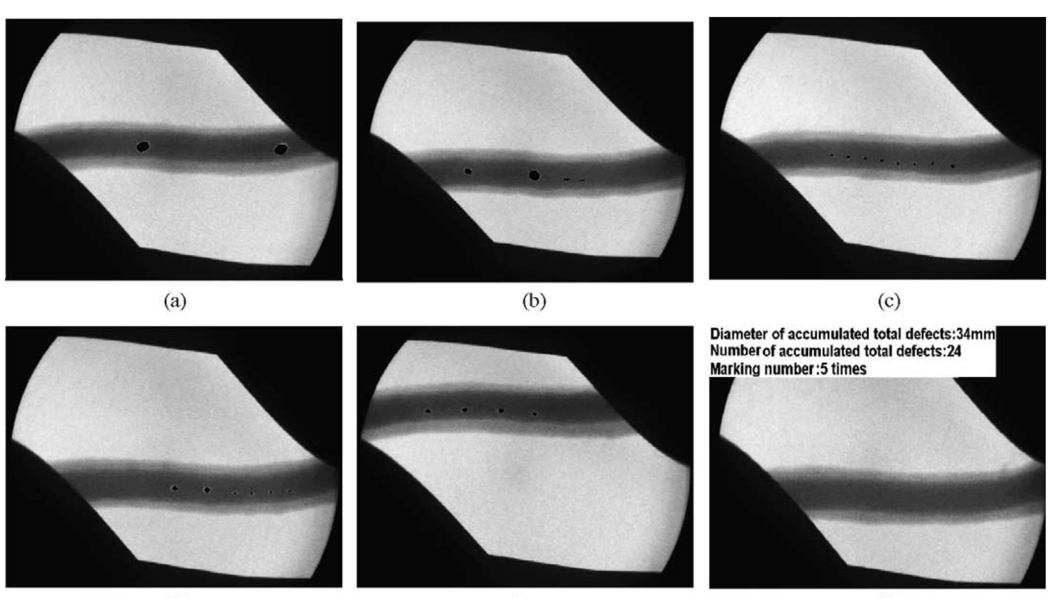

Fig. 7. (a) Two 3.2 mm defects (b) one 3.2 mm defect, one 1.6 mm defect and two 0.8 mm defects (c) eight 0.8 mm defects (d) two 1.6 mm defects and four 0.8 mm defects (e) four 1.6 mm defects (f) total statistical chart of detecting result of each steel tube.

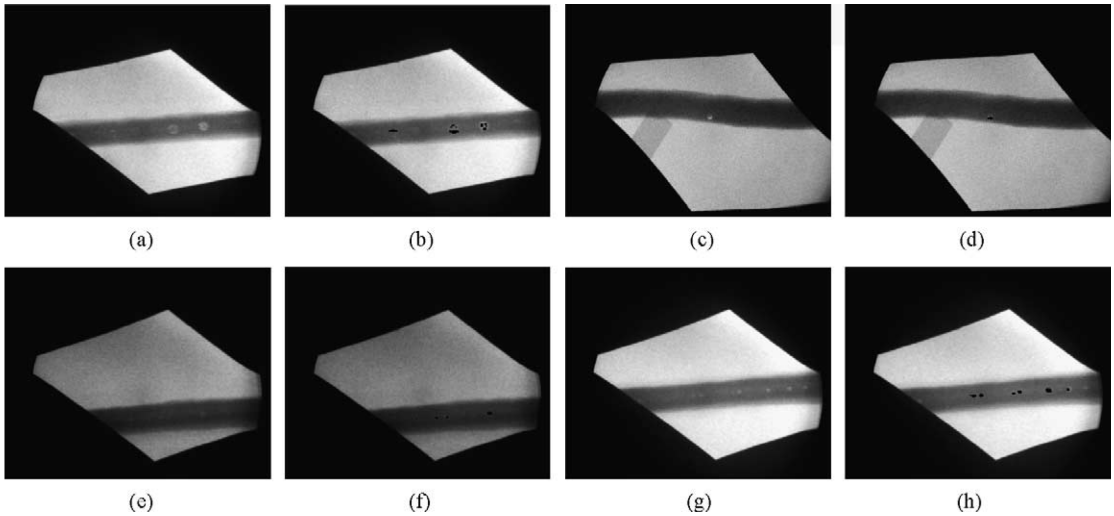

Fig. 8. (a, c) Original image of slags (b, d) detected image of slags (e, f) original image of slags (g, h) detected image of porosities.

4. Experimental results

The above method has been tested on a set of welds with typical defect types (porosities, slags, incomplete penetration), we mainly conduct three aspects to prove the capability of the system, such as the experiments in the lab, practical test and application in the steel pipe factory and acceptance acknowledge of the experts.

4.1. The experiment in the lab

A tape recording weld defects that lasts about 15 min is recorded from factory. The video output from tape recorder is digitized by image grabber. There are 66 defects in the tape. The system successfully detects 65 defects, a very small defect located near dark welded boundary is not labeled by the proposed algorithm, and two misinterpretations that noise regions are regarded as defects occur. So the misreport rate is 3% and the fail to report rate is 1.5%.

4.2. Testing with the sample pipe in factory

A sample steel tube including five kinds of typical defect groups is made. The total length of each kind of defect group is 152.4 mm. The sample tube is detected in real-time. The system has found out all five groups of defects and marked each defect with black dots. Then it calculates the accumulated diameter of the defects in every group, and gives the accumulated total diameter and the number of all defects. At this detection, the system finds out that every group accumulated diameter of the defects reaches the minimum standard, so it alarms and sends out the marking signal. The detecting results are shown in Fig. 7. In this experiment, the accuracy rate achieves 100%.

4.3. Application in the factory

In the factory, we had run the system for more than half a year. The workflow is shown as Fig. 1. We have detected several kinds of defects, such as porosities, slags, incomplete penetration. A total of 216 was selected, among which 136 are porosities, the smallest of which is 400 μm, 75 are slags, five are incomplete penetration. The performance of detection is equal to the evaluation of a human operator. In Fig. 8, we will show some images of actual detection. As an illustration of the whole method, we take five examples of incomplete penetration, which is a typical type of weld defect quite hard to detect. Fig. 9(a and c) shows a part of such a raw image; Fig. 9(b and d) shows detected objects denoted by black line.

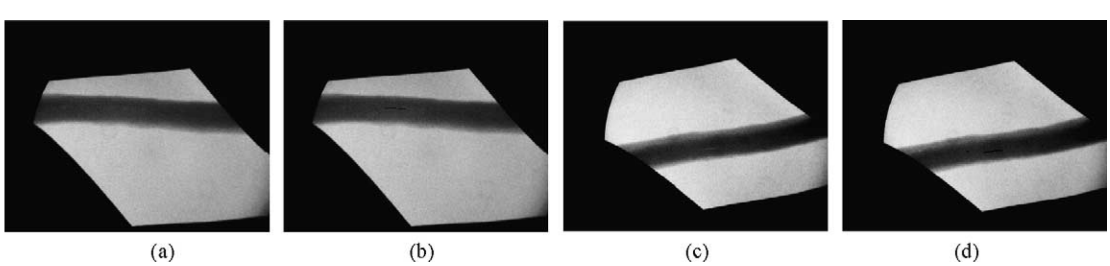

Fig. 9. (a, c) original images of incomplete penetration (b, d) the results of detection.

5. Conclusion

X-ray weld seam automatic detection system recommended in this article applies defect detection algorithm based on fuzzy rules to identify defects in welded seam. It can give a very high confidence about the defect, but rough information on type. The proposed method based on fuzzy rules avoids many drawbacks of traditional approaches.

The major advantages of this method are as follows:

1. It is fast. The detection speed of the system achieves 3.5 m/s, equal to 3–4 frames/s. It can meet the requirement of real-time detection.
2. It is easy. The fuzzy recognition algorithm is easy to understand and at a similar level to human vision.
3. It is flexible and adaptive. It is more effective for defects with different spatial contrast and almost need not change parameter for different X-ray source systems.
4. It is stable and precise. The system has high accuracy rate and low misreport rate.

Our system has obtained a good performance, but we cannot say it is absolutely superior to others studies. Because different sets of radiographic images are used in different studies, this calls for the need to establish a benchmark image set in order to perform a sensible comparison.

Not only our system is designed for detecting the weld seam of steel pipe, but also it is appropriate to other fields, such as other weld seam detection, internal defects detection of mental material and chemical engineering material, critical component detection of car, train and aerospace vehicle. In the future work, we should concentrate on the improvements of imaging aspects and image processing.

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