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Automated Acquisition and Analysis of Digital Radiographic Images

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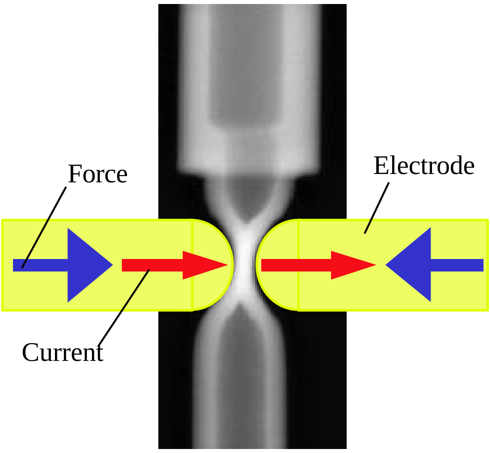
Abstract

Engineers at the Savannah River Technology Center have designed, built, and installed a fully automated small field-of-view, lens-coupled, digital radiography imaging system. The system is installed in one of the Savannah River Site's production facilities to be used for the evaluation of production components. Custom software routines developed for the system automatically acquire, enhance, and diagnostically evaluate critical geometric features of various components that have been captured radiographically. Resolution of the digital radiograms and accuracy of the acquired measurements approaches 0.001". To date, there has been zero deviation in measurement repeatability. The automated image acquisition methodology will be discussed, unique enhancement algorithms will be explained, and the automated routines for measuring the critical component features will be presented. An additional feature discussed is the independent nature of the modular software components, which allows images to be automatically acquired, processed, and evaluated by the computer in the background, while the operator reviews other images on the monitor.

System components were also a key in gaining the required image resolution. System factors such as scintillator selection, x-ray source energy, optical components and layout, as well as geometric unsharpness issues are considered in the paper. Finally the paper examines the numerous quality improvement factors and cost saving advantages that will be realized at the Savannah River Site due to the implementation of the Automated Pinch Weld Analysis System (APWAS).

Background

At the Savannah River Site, a U.S. Department of Energy facility, a joining technique called "pinch welding" is used to seal highly pressurized containers, known as reservoirs. Pinch welding seals the tube by applying high force and high current over time to heat a portion of the metal tube to the plastic state, deform the tube, and ultimately seal the tube. *Figure 1.*



Pinch Weld

Figure 1

Because it is not possible to perform destructive testing of the pinch welds sealing the reservoirs, the qualification process begins with a weld development cycle where welding techniques are developed. Development welds are pressure tested and then destructively analyzed. At the completion of the weld development cycle the acceptable ranges for physical characteristics of the qualified weld are recorded and used as acceptance criteria for production welds.

The key physical characteristics of these pinch welds are:
- minimum wall thickness,
- closure length,
- electrode alignment,
- tube alignment, and
- open bore length.

Each characteristic is described in detail below.

Since the inception of the program, conventional film radiography has been the method utilized to obtain the physical characteristics of the pinch welds. Film radiography is an expensive and labor intensive method to perform this evaluation; however, quantitative data was a prerequisite prior to component acceptance. Until recently it was not possible to obtain the required radiographic sensitivity and spatial resolution required for these evaluations with digital radiography; however recent developments in large format CCD imaging cameras have made this project possible. The authors presented the customer an opportunity to install a state-of-the-art imaging device that would provide improvements in quality factors as well as yield considerable cost savings. The customer immediately supported a program to evaluate, develop, and install the high resolution imaging system.

System Overview

The most important aspect of any automated digital radiography imaging system is x-ray image quality. Without a sharp, high resolution, high sensitivity radiographic image the accuracy of the automated measurements is very low, and may even be useless. Therefore considerable thought must be given to the selection of the x-ray components, the scintillating detector, and the optical components. Furthermore, the geometric unsharpness of the x-ray image must be considered to ensure that unsharpness is the lowest practicable value. (The lower the geometrical unsharpness, the better the image resolution.)

Each of these factors was considered in the design and development of the system, and each will be discussed in this section. The following section discusses the software that processes the images created by the digital radiographic system.

The system is a classical lens-coupled digital radiography system. The x-ray source is a 150 kVp, 3 mA Varian x-ray tube with a 1.5 mm spot size. The tube is housed in an interlocked x-ray cabinet with an imaging chamber 16” x 18” x 48”. A 2” x 2” x 6mm Industrial Quality, Inc. (IQI)-401 terbium-doped high-density glass scintillator was selected to provide high resolution x-ray to light conversion. A 26” source to scintillator distance, with an object to scintillator distance of one-eighth inch yields a geometric unsharpness of 0.29 mils, which is over three times sharper than the optical resolution of the system.

The scintillator was placed slightly out of the center of the x-ray cone beam to allow room for all of the production components to fit in the cabinet. The plane of the scintillator was therefore tilted at an 5 degree angle toward the x-ray spot ensuring that the scintillator plane is perpendicular to the incident x-rays. This maintains the sharpest possible images for this geometrical arrangement.

The optical imaging components are commercially available. A double turning mirror technique was used protect the CCD camera from high-intensity x-rays. The base optical breadboard table and the scintillator shelf are both lead-backed, and a riser connecting the two tables is also backed with lead. This totally shields the camera from direct exposure, thus nearly eliminating x-ray hits to the camera. The camera is a Photometrics Series 300 camera head with a KAF-4200 CCD. The KAF-4200 is a scientific grade 2,000 pixel by 2,000 pixel imager selected specifically to provide 0.001” resolution with a 2” x 2” field-of-view.

The calibrated optical resolution of the system is 0.927 mils, exceeding the stated customer requirement. The pinch weld essentially is in contact with the scintillator during image acquisition; therefore system geometric enlargement is one.

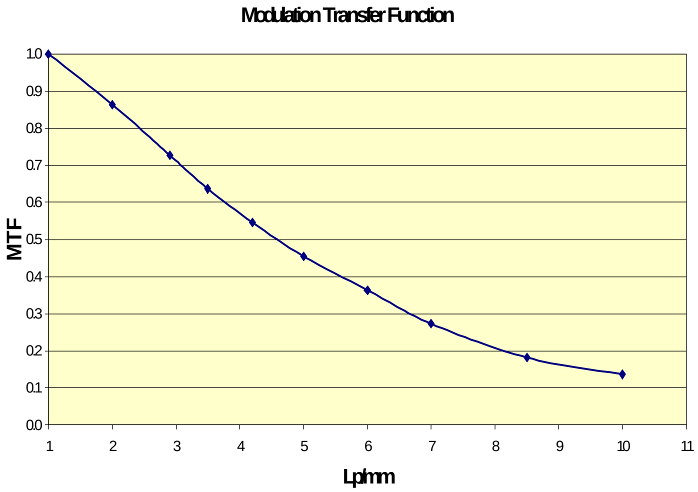


Figure 2

Figure 2 shows the measured Modulation Transfer Function (MTF). The system MTF is approximately 10 lp/mm at 14% modulation.

The system, as designed and installed, provides high spatial resolution images with high contrast sensitivity and a dynamic range far greater than that of conventional x-ray film.

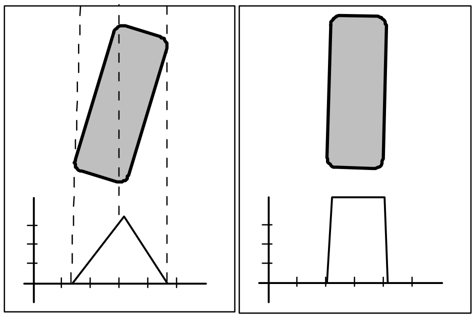
Automated Software Modules

Once a high quality radiographic image was assured, the next step was to automate the acquisition and analysis of the image to provide accurate measurements of all pertinent pinch weld features. The software to accomplish these tasks has been designed in modular form, and will be described in detail for each of four modules. The four modules are Acquisition, Processing, Analysis, and Review. It is important to note that each module runs independently and concurrently. After the image is acquired it is passed to the processing module, and from the processing module to the analysis module. Following the automated computer analysis, a qualified operator reviews the image and the measurement results and makes the final accept/reject decision.

Acquisition Module

An innovative feature of the software is that prior to evaluating each group of reservoirs, an ASTM penetrameter is imaged. The #5 penetrameter is placed on a 60 mil thick steel shim, imaged, and automatically evaluated by the software. The evaluation includes verification of the visibility of the 1T hole, where the software evaluates the contrast change from the area surrounding the 1T hole versus the contrast in the hole, and then evaluates the ratio versus a defined threshold. In addition, the dimensional verification of the pixel size is performed by tracing the penetrameter edges and measuring the diagonal dimensions of the penetrameter. These measurements are compared to National Institute of Standards and Technology (NIST) traceable values. If measurements are outside a pre-defined range of values, imaging tests are halted until the discrepancies are resolved.

The operator then places the reservoir in a fixture that precisely places the pinch weld on the surface of the scintillator. The fixture, however, does not align the pinch weld parallel to the x-ray beam, and therefore the vertical pinch weld alignment is dependent on the operator. To ensure that each image is properly rotationally aligned, the software checks the alignment by evaluating the slope of the line profile at the center of the pinch. Essentially, the center of a pinch is similar to a rectangle, and for high resolution imaging of the pinch weld the "rectangle" must be precisely aligned with the path of the x-ray photons. *Figure 3*. If the rectangle is misaligned, the slope will be less, and the operator will be prompted to realign the pinch weld.



Misaligned Aligned

Figure 3

This alignment procedure is performed on a low resolution "postage stamp" image that requires only 15 seconds to acquire. This postage stamp image is also used to define the region of interest (ROI) that is required for the full resolution image. A very small amount of the 2" x 2" field-of-view (FOV) is required to image the tube, therefore to save data storage space only the required data is acquired and archived. This ROI is automatically detected and set by the software for each image (the ROI changes depending on the reservoir being evaluated). The software also extracts the pinch weld characteristics to determine which measurements will be performed in the analysis module. When the alignment is acceptable and the operator has verified proper ROI placement, the software begins a four minute exposure to acquire the full resolution image. Following the acquisition the image data is presented to the processing module for data processing.

Processing Module

De-fog

A “de-fogging” algorithm is applied to the recently acquired pinch weld image, I_0, and to the background image, I_B, that was acquired at the beginning of the run sequence. The de-fogging routine is used to remove effects of x-ray scatter and scintillator cross talk in the background image and the pinch weld image. Incident x-rays transmitted through the pinchweld generate the light in the scintillator that makes up the true image, however light is also generated by scattered x-rays. Further, the light in the transparent scintillator is transmitted in three dimensions, thus there is light “cross talk” for neighboring pixels within the scintillator. The closer the pixels are together, the greater the cross talk effect. The algorithm effectively removes both the scatter effect as well as a large portion of the cross talk effect. *Figure 4* shows the light generation components of a single scintillating pixel. The x-ray intensity transmitted through the subject, I_{Tx}, the x-ray scatter intensity incident upon the pixel, I_S, and the cross talk light, L_X, all contribute to the total light, L_T, detected by the camera at that pixel.

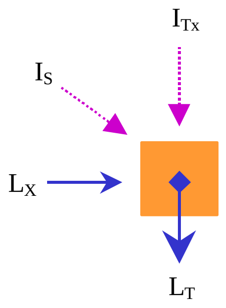


Figure 4

$$L_T = L_{I_{Tx}} + L_{I_S} + L_X \qquad \text{(Eq. 1)}$$

The desired light to be detected is L_{ITx}, therefore the effects of all extraneous light must be removed from the data. This is accomplished using the equation

$$L_{I_{Tx}} = L_T - \sum_i \sum_j F(i,j) * L_T(i,j), \qquad \text{(Eq. 2)}$$

where a function, F(i,j) scales the effect of the total light, L_T, generated in neighboring pixels for a two dimensional surrounding area, i by j. F(i,j) reduces the effect as the distance away from the pixel increases.

The effects of the de-fog routine are tremendous. The edge definitions in the image are greatly enhanced due to the removal of the low frequency cross talk between neighboring pixels. Further, the contrast within the part is greatly increased. *Figure 5* shows a comparison of the de-fogged image (bottom) versus the unprocessed image (top). Comparison of the contrast curves taken through the base, the pinch, and the tube show the increased contrast, the more defined edges, and the removal of the low frequency shadowing apparent near the edges of the tube.

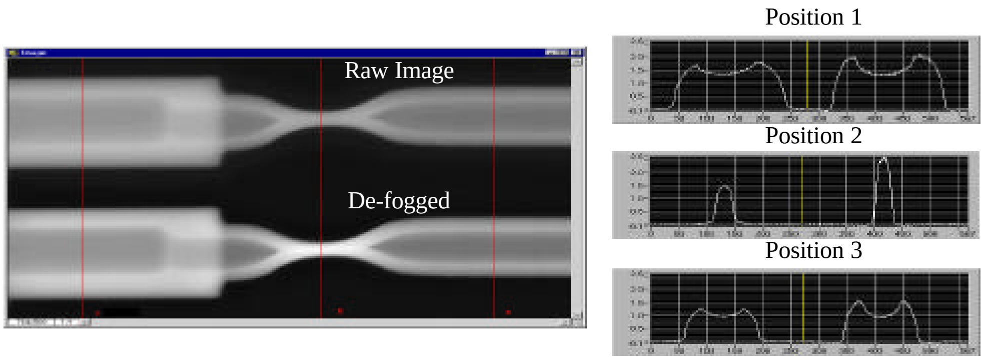


Figure 5

Background and Dark Correction

Beer's Law,

$$I_R = \frac{I_B' - I_D}{I_0' - I_D} \quad , \qquad \text{(Eq. 3)}$$

is applied with the de-fogged background image, I_B', and the dark image, I_D. I_0' is the de-fogged full resolution pinch weld image. Beer's Law processing removes effects such as scintillator imperfections, optical aberrations, differences in pixel responsiveness, as well as other system abnormalities. I_R is the resultant image data.

De-speckle

In the final step of the processing module, the de-speckle routine is applied to I_R. The de-speckle routine is used to remove "bad" pixels or pixels that have been over-exposed due to a direct strike of an x-ray photon. The center pixel being evaluated, P_C, is compared to the eight surrounding pixels. If P_C is greater than the median surrounding pixel by a specified threshold, then P_C is replaced with that median pixel value.

The processed image is now ready for automated analysis, and is placed in the analysis module's cue.

Analysis Module

Two analyses are performed on the radiographic data. The first is the quantitative measurements of the weld characteristics performed here in the Analysis Module. The second is actually completed by the operator in the Review Module. The operator visual verifies the automated measurements, and then visually examines the tube and the weld area for defects.

The quantitative evaluations are automatically performed by the computer using custom developed software to define the characteristics and then measure the parameters. Four edges form the basis from which all measurements are determined. These edges are the left and right outer edges of the tube, and the inner edges on the reservoir side of the pinch weld and on the open side of the tube.

The outer edges are determined by simple intensity thresholding. The edge is detected at a percentage level above the background contrast level. The inner edges are set by a slope threshold method. The slope threshold method detects an inner edge by first finding the zero-slope point for the tube's contrast curve. The inner edge is then set at a point a percentage below the zero slope on the row's contrast curve. Both threshold levels were set and verified by comparison to a calibrated "standard tube." As stated previously, all edge detection levels have been set, calibrated, and verified numerous times.

With the edges defined, all parametric measurements can be determined. There are presently seven parameters that are automatically determined by software. These are:

Minimum Wall Thickness

Minimum wall thickness is a critical process parameter that measures the thinnest portion of the tube wall on the reservoir side of the weld. The minimum wall thickness measurement must be greater than that specified for the reservoir being evaluated. The minimum wall thickness is determined by measuring the distance from every point on the reservoir inner wall edge to every point on each of the outer wall edges. The minimum wall thickness value is extracted from these measurements.

Weld Closure Length

The weld closure length is the minimum distance between the reservoir inner edge and the open-end inner edge. This measurement is obtained by determining the distance from every point on the reservoir inner edge to every point on the open-end inner edge, and then extracting the minimum value. This value therefore measures the minimum closure length of the pinch weld. The designer specifies the minimum length, and the measurement must be greater than the specification for the unit to be accepted.

Electrode Alignment

The electrode alignment parameter measures the vertical alignment of the two electrodes used to make the weld. The alignment is critical because electrodes greater than the acceptable offset could cause a failure of the weld process resulting in considerable expense. The software calculates the offset by first generating a best-fit "electrode" from the pinch region of each outer edge. A line is then extended from the center of the "electrode" toward the center of the electrode's deformation in the pinch. The measurement is the offset measured at the vertical centerline of the pinch.

Tube Alignment

The tube alignment measurement is a measurement of the angular difference of the tube extending from the pinch to the reservoir versus the tube extending from the pinch to the open end. This parameter is determined by measuring the angular difference between projected centerlines generated from the outer edges above and below the pinch area. The customized software provides additional information, the tube-centerline offset value. The value is the offset of the centerlines when extended vertically to the center of the weld.

Open Bore Length

Open Bore Length is the location where the inner edge diameter drops below a threshold specified by the designer. This measurement is acquired by defining two value, the location where the tube extends from the reservoir base, and the point at which the reservoir inner edge separation (tube I.D.) drops below the threshold.

Review Module

The Review Module is somewhat of an extension of the Analysis Module, however the two run independently and therefore are considered separate modules. The Review Module is the most interactive module requiring the operator not only to verify the placement of the inner and outer edges, and the location of the measurements, but also perform a visual inspection of the radiographic image.

Although the software has been thoroughly tested, the designers believed that at least initially the operator should be required to verify the placement of the edges and concur with the locations of the measurement values. Therefore, when the operator reviews an inspection, he is presented with the edge traces and each measurement visually. He either accepts the parameter or rejects the parameter with a comment. The parameter cannot be rejected without a comment explaining the concern. This allows the production engineer to key in on an anomaly during a subsequent examination.

Operators performing the visual examinations must be minimally qualified as an ASNT limited level II x-ray technician. The operator is presented the processed image with mathematically generated 1T holes placed on mathematically generated shims ranging from 30 mils to 150 mils. The virtual #5 penetrameter 1T hole ensures the contrast sensitivity of the system. The extended dynamic range of the digital radiograph contains qualitative data throughout this large range of material thickness, unlike the conventional film method that was qualified for material thickness of only 50 to 78 mils. This alone is a leap forward in the qualitative evaluation of the weld area, which has a material thickness of greater than 120 mils.

The system allows the operator to vary the contrast levels, while viewing the pinch weld image and the 1T penetrameter "swatches." The operator has the ability to reduce the display intensity range to produce a higher contrast in a limited range, or expand the range to produce an image similar to film. By ranging through the entire range of contrast levels the operator performs a very thorough evaluation of the tube as well as the weld area. Again, the operator is permitted to comment on anomalies. These comments are written to the file history and permanently stored with the image data.

Results

The installation of the automated digital radiography system provides many benefits to the customer in this application. The two key benefits are quality improvement and cost savings. Both are obviously critical factors when any organization attempts to justify the installation of a capital piece of equipment.

Quality Improvements

Calibrated Measurements

The Automated Pinch Weld Analysis System (APWAS) measurements are calibrated and traceable to NIST. On the other hand, there is no way to provide calibration of an operator subjectively determining the edges of the x-ray image, and then performing the measurement of the characteristics.

Greater Measurement Repeatability

The automated measurement algorithms provide zero variation in repeated measurements of the same image, and assures consistent evaluation of pinch welds throughout the life of the system. The conventional method of operator evaluation yielded greater than 25% variation in measurements from operator to operator for evaluations of the same radiographic images.

More Thorough Radiographic Evaluation

The APWAS provides code quality evaluation of the pinch weld radiograph throughout the required thickness range (i.e. 0.030" - 0.130"), and allows the operator to change the contrast levels for a more through evaluation. The conventional method was set up to radiographically image the pinch weld to allow for evaluation of the pinch weld characteristics (0.050" - 0.070"), not for anomalies in the weld area (0.125").

Process Control Feedback

The APWAS allows the operator to evaluate the image within minutes of the exposure, and provides the pinch weld characteristic measurements within minutes as well. If there is an unacceptable parameter, the process can be immediately evaluated and the problem corrected prior to additional reservoirs being sealed. This valuable feedback can typically take two weeks with the conventional film method currently in use.

Cost Savings

Reduced Labor Expenses

Time is money, and labor hours consume budgets. This first installation of the APWAS will have a considerable effect on reducing the labor required for analysis of these welds, however the larger savings will be realized following the conversion of an additional three locations to digital systems. At that point, due to the automated nature of the system, full-time subcontract radiographers will no longer be required at the facility, saving well over a $100,000 per year. Further, due to the contaminated nature of the inspection location, no longer will Radiation Control specialists be required to “bag-in/bag-out” film because the digital images will be digitally transmitted from the camera to the computer. In all, labor savings alone are estimated to total over $250,000.

Reduced Film Evaluation Time

Since the parameters are automatically measured by the software, no longer do operators have to laboriously determine several measurements for each pinch weld film, moving from two different measurement instruments. Due to the automated and modular nature of the software the operator can be performing other tasks while the computer is imaging, processing, and analyzing images.

Reduced Film and Chemical Requirements

A considerable cost savings will be realized due to the reduced need for x-ray film and development chemicals. Although this cost savings will not scale to the magnitude of the labor savings, this benefit is also important to reduce resource consumption and reduce waste streams.

Reduced Number of “Rejected” Units

If a parameter is outside of an acceptable range, the reservoir is rejected and the unit must be “re-worked.” This is a very timely and costly process extending into the hundreds of thousands of dollars. The immediate feedback of the APWAS will reduce the number of “re-work” units, thus providing considerable cost savings as well as process quality improvement.

Additional Benefits

Digital Nature

There are obvious advantages of the system being digital, such as the data being stored on compact storage disks, replacing film and paper storage. An additional feature of digital storage is that the digital data never degrades, unlike film which will fade over time. Further, the digital images and measurement data may be quickly shared electronically for evaluation and discussion.

Reduced Waste Streams

As mentioned above, the complete installation of the APWAS will eliminate the "bag-out" scenario and reduce that waste stream, as well as the reduction of waste film and development chemicals.

Summary

Throughout the development of the APWAS several advances in digital radiography techniques have been developed. A key breakthrough is the de-fogging algorithm that removes cross talk effects that have plagued glass scintillators, thus increasing attainable resolution. The display of the "virtual" penetrameter to ensure equivalency to film is another development in the presentation of digital x-ray images. This "virtual" penny display allows for code-quality examination of the entire dynamic range of the digital data.

In conclusion, the pinch weld image acquisition and analysis system is a production-ready system with customized, automated software that controls the imaging and analysis process through the complete imaging cycle. The system delivers accurate, repeatable, digital results by eliminating operator bias in the imaging process as well as the analysis processes.