Analysis of ASTM X-ray shrinkage rating for steel castings

K. Carlson†*, S. Ou†, R. Hardin† and C. Beckermann‡
†*Research Engineers, Department of Mechanical Engineering, The University of Iowa, Iowa City, IA*
‡*Professor, Department of Mechanical Engineering, The University of Iowa, Iowa City, IA*

This paper presents the results of two different studies that examined the ASTM x-ray shrinkage rating system for radiographs of steel castings. The first study evaluated the repeatability and reproducibility of x-ray shrinkage ratings through a statistical study of 128 x-rays that were each rated seven different times. It was found that the seven ratings for each x-ray were in unanimous agreement on both shrinkage type and level for 12.5% of the x-rays. All of the x-rays that had unanimous agreement for both type and level were either completely sound or very unsound (Level 5). The largest variance was found to occur in Level 2 and 3 x-rays, which had 95% confidence intervals of about ±2 x-ray levels. The average 95% confidence interval for all 128 x-rays was ±1.4. The second study involved an effort to determine the shrinkage severity level of x-rays through digital analysis of scanned radiographs. It was found that defect area and circumference correlated reasonably well with x-ray level, but only if the shrinkage type was correctly determined first.

Keywords: ASTM x-ray, shrinkage rating, radiography

Introduction

Radiographic testing is a common measure of casting quality employed in the steel casting industry. Many production castings are either accepted or rejected based on their radiographic testing (RT) levels of various discontinuities, such as gas porosity, inclusions and shrinkage. However, RT levels are determined in a somewhat subjective manner. X-rays of casting sections are assigned a severity level for a particular type of discontinuity through comparison with ASTM standard radiographs for steel castings. These radiographs are included in ASTM standard E446 for castings up to 2 inches thick,[1] E186 for castings 2 to $4\frac{1}{2}$ inches thick,[2] and E280 for castings $4\frac{1}{2}$ to 12 inches thick.[3] Each of these three standards provide reference radiographs that are grouped by discontinuity category. Category A is assigned to gas porosity, Category B is sand and slag inclusions, and Category C is shrinkage. Shrinkage is further subdivided into types CA (individual veinous strands of shrinkage), CB (grouped or connected veinous strands; almost tree branch-like) and CC (spongy appearance). For sections less than 2 inches thick (E446), there is also a type CD (similar to CB, but more dense and compact). Category A, B and C discontinuities are all divided into five severity levels (1–5, severity increases as the number increases), and there are reference radiographs for each level of each type of discontinuity. In addition to Categories A, B and C, there are also categories for cracks, hot tears, etc. These categories, however, are not divided into severity levels.

To assign a severity level to a particular kind of discontinuity on a production x-ray, it is first necessary to determine what type of discontinuity it is. This is not always easy, and can be complicated further when more than one type of discontinuity (e.g., shrinkage and sand) is present. Furthermore, if it is determined that the discontinuity is shrinkage, it is also necessary to determine what kind of shrinkage. Once the discontinuity has been categorized, the production x-ray is compared to the reference radiographs for that discontinuity. The highest level of reference radiograph that the production x-ray has a severity better than or equal to is the severity level assigned to that x-ray. If the severity level of the production x-ray is worse than Level 5, it is assigned Level 5.

This radiograph comparison process may sound relatively straightforward, but there are several issues that complicate the comparison. First, the discontinuities on a production x-ray may be distributed in a manner that is quite different from the reference radiographs. For example, the reference radiographs for shrinkage have a relatively uniform shrinkage distribution. However, shrinkage on production x-rays is frequently non-uniformly distributed. A good example of this is centerline shrinkage. To determine a severity level in this case, a representative ''area of interest'' on the production x-ray, containing the centerline shrinkage and an unspecified amount of the surrounding sound region, must be chosen to compare with the standard. The arbitrary choice of the ''area of interest,'' combined with the difficulty in objectively comparing the severity of a uniform pattern to a highly non-uniform one, complicate the determination of severity level. Second, the comparison is supposed to be made using an area of similar size to the reference radiograph. If the area of interest in the production x-ray has a different size, this area is supposed to be prorated to the area of the reference radiograph. This requirement of the radiographer to mentally prorate an area and then compare severity further decreases the objectivity of

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*Author for correspondence
e-mail: kent-carlson@uiowa.edu

this determination. Finally, for Category A and B discontinuities, the standards state that the radiographer should not evaluate severity based solely on the size, number or distribution of discontinuities. Rather, the total area of the discontinuities in the production x-ray should be compared to the total area in the reference radiograph. For example, a production x-ray may have larger gas pores than a reference radiograph, but the gas porosity level may still be less severe than the reference if there are fewer pores in the production x-ray. Trying to visually compare total discontinuity areas by considering size, number and distribution is not a simple task.

Because the decision of whether to accept or reject a casting is often based on these relatively subjective severity levels, it is of interest to quantify the variability involved in assigning RT (or x-ray) levels to a casting x-ray. Quantrell[4] performed a study of the variability of x-ray shrinkage rating using radiographic records from 34 casting defects. Five trained radiographers independently evaluated the x-rays, and the results were compared for consistency in shrinkage type and shrinkage level. With respect to shrinkage type, Quantrell noted that several radiographs had types CA, CB and CC assigned to the same indication. He found that there was more distinction between type CC and the other types, especially at higher severity levels. At lower severity levels, he concluded that type categorizing was very difficult to do with any degree of reliability. With respect to shrinkage level, 6 of the 34 radiographs (18%) were rated with the same level by all five radiographers, and all of those were either Level 1 or Level 5 ratings. Quantrell concluded that Level 3 was the most inaccurately defined level, and that the severity level rating system has a variability of ±1 level. He also made a noteworthy point, however, in stating that in an accept/reject situation in a foundry, the radiographer only has to compare the production x-ray with one standard radiograph and decide if the defects in the production x-ray are better or worse. For example, if the acceptance criterion is Level 2 or better, it does not matter if the radiographer thinks the production x-ray defect level is Level 3 or Level 4, because both of those would be rejected. This situation should reduce the variability in shrinkage level rating, to some degree.

The uncertainty inherent in the current procedure of x-ray level assignment is critically important when one considers the fact that this assignment literally determines the fate of the corresponding casting (or group of castings). With this in mind, it seems prudent to develop a more quantitative method for determining x-ray level. One possible alternative is presented in this paper: a method that assigns ASTM shrinkage severity levels to digitized x-rays based on quantitative defect measurements. The information provided here is not the final solution to the problem. Rather, it is intended to serve as groundwork for future studies, highlighting some of the concerns and difficulties that arise and offering ideas for handling these issues whenever possible. The present authors are unaware of any similar work being done in this area.

The next section of this paper describes the results of a study inspired by Quantrell's work. 128 x-rays were rated by five radiographers, two of whom rated all of the x-rays two different times. This study was performed to validate and expand on Quantrell's findings, in order to gain further insight into the repeatability and reproducibility of x-ray shrinkage ratings. Following the statistical study, the quantative digital x-ray analysis algorithm mentioned above will be presented and discussed.

Repeatability and reproducibility of x-ray shrinkage ratings

The present x-ray shrinkage rating study involved 128 radiographs from the first SFSA/University of Iowa steel plate casting trials.[5,6] In these casting trials, four foundries cast 3″ thick × 6″ wide plates, and one foundry cast 1″ T × 5.5″ W plates. Each foundry cast plates of various lengths that were selected to produce castings ranging from completely sound to RT Level 5 shrinkage. All plates were cast from low alloy steel (1025 steel or similar). X-rays for each plate were then produced according to ASTM E94, the Standard Guide for Radiographic Testing.[7] Although all of the x-rays were produced according to the same standard, different foundries used different x-ray equipment, film, etc. To determine if these differences influenced the variability of x-ray ratings, the results were analyzed by foundry as well as overall. This will be discussed briefly with the results of the study.

The casting foundry provided the initial evaluation of ASTM shrinkage type and severity level. This was performed by either a radiographer at the foundry, or by a radiographer working for a company that evaluates radiographs. In the results, this initial x-ray rating is referred to as ''Radiographer 1'', even though a different radiographer evaluated the x-rays for each foundry. Then the x-rays from all five foundries were collected and sent to other radiographers for evaluation. Radiographers 2 and 3 each evaluated the x-rays two separate times, and Radiographers 4 and 5 each evaluated the x-rays once. Thus, each x-ray was rated a total of seven times. Radiographers 2 and 3 were Level III Radiographers, and Radiographers 4 and 5 were Level II Radiographers. The x-rays of the 3″ T × 6″ W plates were evaluated using reference radiographs from ASTM E186, and the x-rays of the 1″ T × 5.5″ W plates were evaluated with radiographs from E446. Radiographer 2 also evaluated the x-rays for Category A and B discontinuities, and some of the original foundry radiographers provided A and B ratings as well.

The data from the radiographers' evaluations were then collected and analyzed. For each radiograph, the seven x-ray level ratings were averaged to find the mean x-ray level (Xavg). A one-sided student-t 95% confidence interval (tS_x) was also computed for each x-ray, where S_x is the standard deviation of the seven ratings and $t = 2.447$ is a weighting function accounting for the 95% level of confidence and the small data set size. If the data set size were very large, t would approach 2.0, the value used for 95% confidence intervals for large data sets (two standard deviations). Note that since tS_x is one-sided, the complete 95% confidence interval is twice this value (i.e., the complete confidence interval is Xavg ± tS_x).

In addition to shrinkage severity Levels 1–5, the results presented in this paper add the additional designation of Level 0. Level 0 indicates that the x-ray has absolutely no shrinkage indications (i.e., completely sound). Although this is not an official ASTM classification, making the distinction between completely sound and Level 1 x-rays provides additional information that is useful for the purposes of this study.

Overall agreement of x-ray shrinkage ratings

The occurrence of unanimous agreement between the seven x-ray ratings can be summarized as follows:

- Unanimous agreement in shrinkage type: 47/128 x-rays (37%)
  14 level 0 (no type)
  7 CA
  20 CB
  6 CC
- Unanimous agreement in shrinkage level: 22/128 x-rays (17%)
  14 Level 0
  1 Level 1
  1 Level 2
  1 Level 3
  5 Level 5
- Unanimous agreement in shrinkage type *and* level: 16/128 x-rays (12.5%)
  14 Level 0
  2 CB5

These results indicate that shrinkage type is more readily identifiable than shrinkage level. Unanimous agreement on x-ray type occurred in nearly two out of every five x-rays, while unanimous agreement on x-ray level occurred in less than one out of every five x-rays. Most of the x-rays with unanimous level ratings were either completely sound (Level 0) or very unsound (Level 5). All of the x-rays with both unanimous type and level ratings were either Level 0 or Level 5. These trends agree with the findings of Quantrell,[4] and illustrate the subjective nature of the current x-ray rating system.

Fig. 1 gives additional detail regarding the agreement of the x-ray ratings, listing not only the overall results (rightmost category), but also the results for each foundry. Note that Fig. 1 shows the percentages of x-rays that do *not* have unanimous shrinkage type, level and total ratings, which is the opposite of the data presented above. The percentage of x-rays without unanimous type agreement ranges from 41% in Foundry K to 94% in Foundry S, while the percentage without unanimous level agreement ranges from 50% in Foundry K to 95% in Foundry E. Recall, however, that Foundry K used E446 as the standard (1″ thick plates), while the other four foundries used E186 (3″ thick plates). The use of a different set of reference radiographs for the 1″ thick plates may have contributed to the differences seen in rating agreement. If one considers only the four foundries that cast 3″ thick plates, there are still considerable

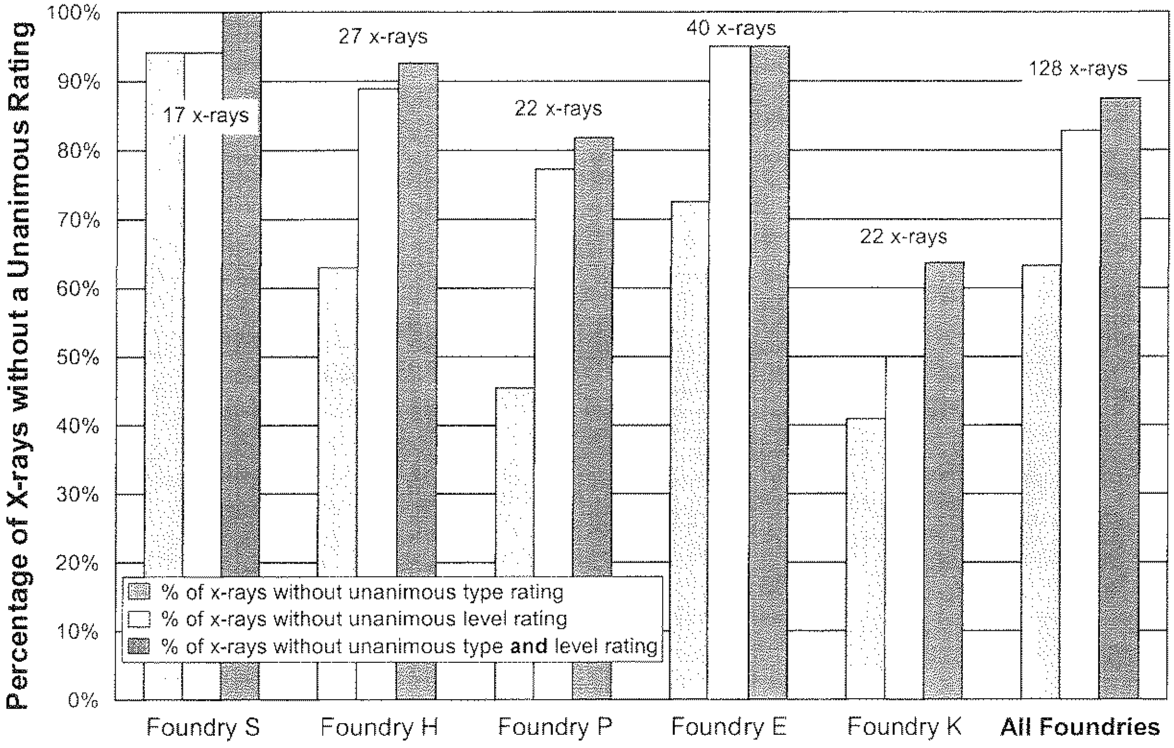

Fig. 1 Percentage of x-rays without a unanimous shrinkage type, level, and total rating, grouped by foundry

Table 1 Worst-case examples of agreement between x-ray shrinkage ratings

	Radiographer 2		Radiographer 3				
Radiographer 1	1st	2nd	1st	2nd	Radiographer 4	Radiographer 5	Category A and B Defect Ratings
0	CB4	CC5	0	CC4	CA1	CA2	B3
1	0	0	CC4	CB1	0	0	B2
CA2	CB3	CB5	CB1	CA2	CA1	CB3	A3, B3
CA3	CB2	CB3	CB1	0	CB4	CB3	none
CA2	CB2	CB3	0	CA3	CC4	CB3	B3
1	0	0	CC4	CB1	CA1	0	B2
0	CB1	CC3	0	CA1	CB4	CB2	B4
0	CB4	CB5	CD5	0	CB1	0	A4, B4

differences in the percentages of plates without unanimous shrinkage type agreement (46–94%), but the percentages of x-rays without unanimous level agreement (77–95%) and total agreement (82–100%) are similar. Based on these results, it appears that ASTM E94 does a reasonable job of minimizing the variability of x-ray level rating due to the actual process of producing radiographs.

A listing of the radiographs with the poorest agreement in x-ray level ratings is given in Table 1. It is interesting to note that all but one of these x-rays had significant indications of Category A and/or B discontinuities as well. It is likely that some radiographers saw discontinuities as either gas or inclusions and thus gave a low shrinkage level, while others determined that the same discontinuities were shrinkage. For the second and sixth x-rays, the foundry radiographer (''Radiographer 1'') did not record the shrinkage type, only the level ''1'').

Variance among x-ray level ratings

Fig. 2 illustrates the variance of x-ray level ratings for the entire set of 128 x-rays. The radiographs were grouped by average x-ray level, and the one-sided 95% confidence intervals (tS_x values) of all the x-rays in each group were then averaged. The average 95% confidence intervals (CI's) are relatively small for the x-rays grouped in Levels 0 and 5. This indicates that, on average, a given x-ray in one of these groups has a relatively small variance among its seven x-ray level ratings. Hence, the radiographers were in the best agreement about x-ray level for Level 0 and Level 5 x-rays. The variance increases for the middle groups, with the Level 2 and Level 3 x-rays having the largest average 95% CI's (2.1

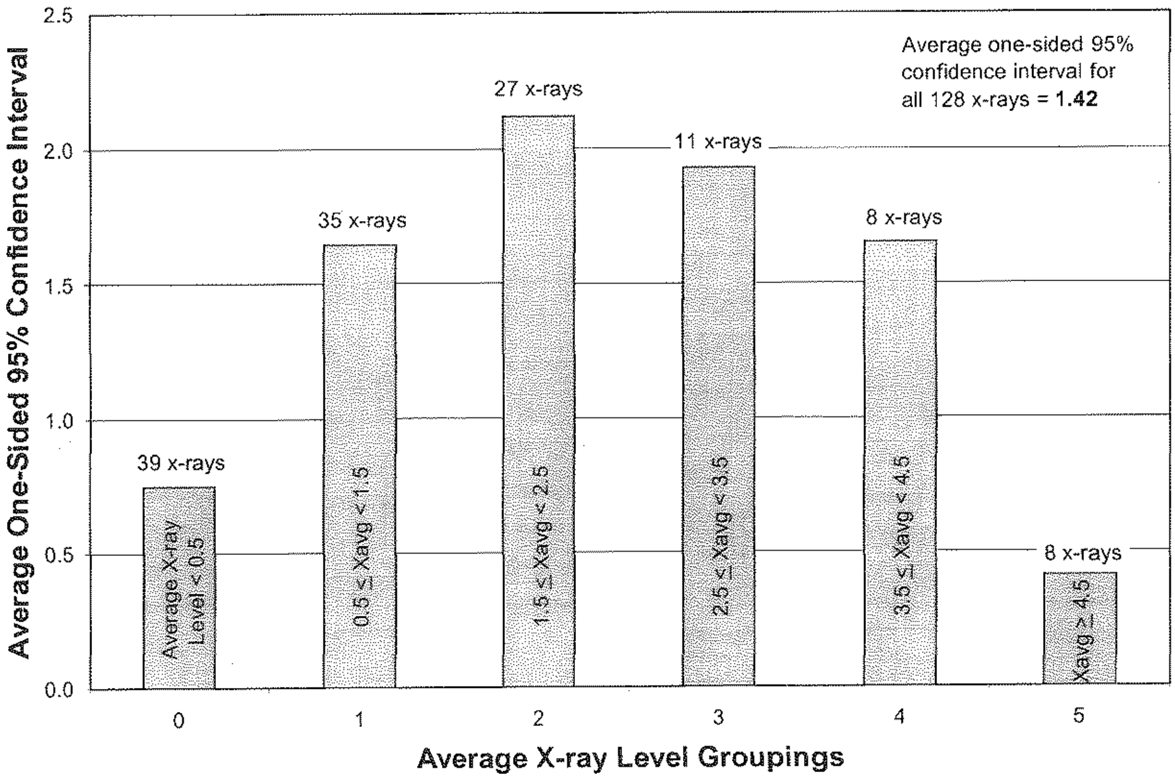

Fig. 2 Average one-sided confidence intervals of x-ray level ratings, grouped by average x-ray level

Table 2 Number of radiographs with x-ray level ratings both above and below accept/reject thresholds

Accept/Reject Threshold	Number of X-rays with Ratings Crossing Threshold	Percentage
Level 1 or better	45 or 128	35.2%
Level 2 or better	32 of 128	25.0%
Level 3 or better	27 of 128	21.1%

and 1.9, respectively). This implies that x-rays in these groups have an average variability of about ±2 x-ray levels.

An argument could be made that the eight x-rays listed in Table 1 are outliers, and should not be considered in these results. If these eight x-rays are removed from the data set and the data in Fig. 2 are re-plotted, the results do not change drastically. The only levels whose average 95% CI's change are Levels 1 and 2. For Level 1, the average CI drops from 1.7 to 1.5 (for 33 x-rays), and for Level 2, it drops from 2.1 to 1.6 (for 21 x-rays). The overall average 95% CI for all x-rays drops from 1.42 to 1.24. Since the results are similar with or without these x-rays, they are left in for the remainder of the analysis.

Variability of x-ray shrinkage level ratings was also investigated in terms of common threshold RT levels specified by customers. Of interest is the number of radiographs that were assigned x-ray level ratings both above and below various threshold values. This implies that the castings associated with these x-rays would have been accepted by some radiographers and rejected by others. Since determining whether a casting is better or worse than an accept/reject threshold is the main reason radiographs are produced, this is a critical issue. Table 2 summarizes the number of radiographs that have x-ray level ratings both above and below threshold values for three common threshold levels. Note that over 20% of the x-rays cross each accept/reject threshold. For "Level 1 or better," 35% of the x-rays would have been accepted by some radiographers and rejected by others.

Repeatability of x-ray shrinkage ratings

Finally, the consistency of the x-ray level ratings by the radiographers who rated all of the x-rays twice was examined. Fig. 3 compares the first and second sets of ratings from Radiographer 2. Each x-ray is plotted as a filled circle, with the first rating as the horizontal coordinate and the second rating as the vertical coordinate. The diagonal line passes through the circles representing the x-rays that were given the same rating both times. The numbers next to the circles indicate the number of x-rays that the circles represent. Radiographer 2 was relatively consistent, giving the same level in both ratings 66% of the time. Notice that there are more x-rays above the diagonal line (36) than below (8). Therefore, when Radiographer 2 gave an x-ray a different level in the second rating, the second rating was usually higher than the first. The summary information in the box in the lower right of this plot indicates that Radiographer 2 was consistent in type rating, giving the same type in both ratings 81% of the time. The total rating (type and level) was the same 59% of the time. The dashed boxes enclose x-rays that Radiographer 2 rated once above the "Level 1 or better" threshold, and once below. The dash-dot-dot boxes enclose x-rays rated both above and below the "Level 2 or better" threshold. Radiographer 2 gave x-ray ratings that crossed the "Level 1 or better" threshold for 12% of the x-rays, and crossed the "Level 2 or better" threshold for 10% of the x-rays.

Fig. 4 displays the results of the two ratings by Radiographer 3. This radiographer was a little less consistent than Radiographer 2 in shrinkage level (same level 56% of the time), and a considerably less consistent in shrinkage type (same 51% of the time). There is also more scatter in the levels assigned by Radiographer 3. The largest difference in levels between the first and second ratings of Radiographer 3 is five (5 first rating, 0 second), and there are several x-rays with a difference of three levels. By contrast, Radiographer 2 never gave a second rating more than two levels from the first rating. Examining the boxes enclosing x-rays that crossed the two accept/reject thresholds considered, Radiographer 3 crossed the "Level 1 or better" threshold for 15% of the x-rays, and crossed the "Level 2 or better" threshold for 9% of the x-rays.

The information presented in this section verifies that ASTM shrinkage x-ray level rating is definitely not an exact science. For Level 2 and Level 3 x-rays, this study found a variability on the order of ±2 levels. The results concerning accept/reject thresholds show that it may not be uncommon for one radiographer to accept a casting while another rejects the same casting. Furthermore, one radiographer looking at one x-ray on two separate occasions may give it an acceptable rating at one time and an unacceptable rating at another. In light of this analysis, it seems evident that a more quantitative, less subjective method of determining x-ray levels would be very beneficial to the steel casting industry. The next section describes a study that attempts to develop such a quantitative methodology for the determination of shrinkage x-ray levels.

Digitized x-ray analysis

The objective of the digital x-ray study was to use image analysis of ASTM reference radiographs to establish quantitative relationships between shrinkage defect measurements and ASTM x-ray level. Once established, these relationships could then be used to evaluate x-ray levels from digitized images of casting x-rays in a more objective manner. If successful, this methodology could be used to improve or revise the ASTM standards utilized to determine shrinkage x-ray levels. In the first part of this study, ASTM reference radiographs were digitized, and different defect measurements were evaluated to determine if they correlated to x-ray shrinkage levels. Once

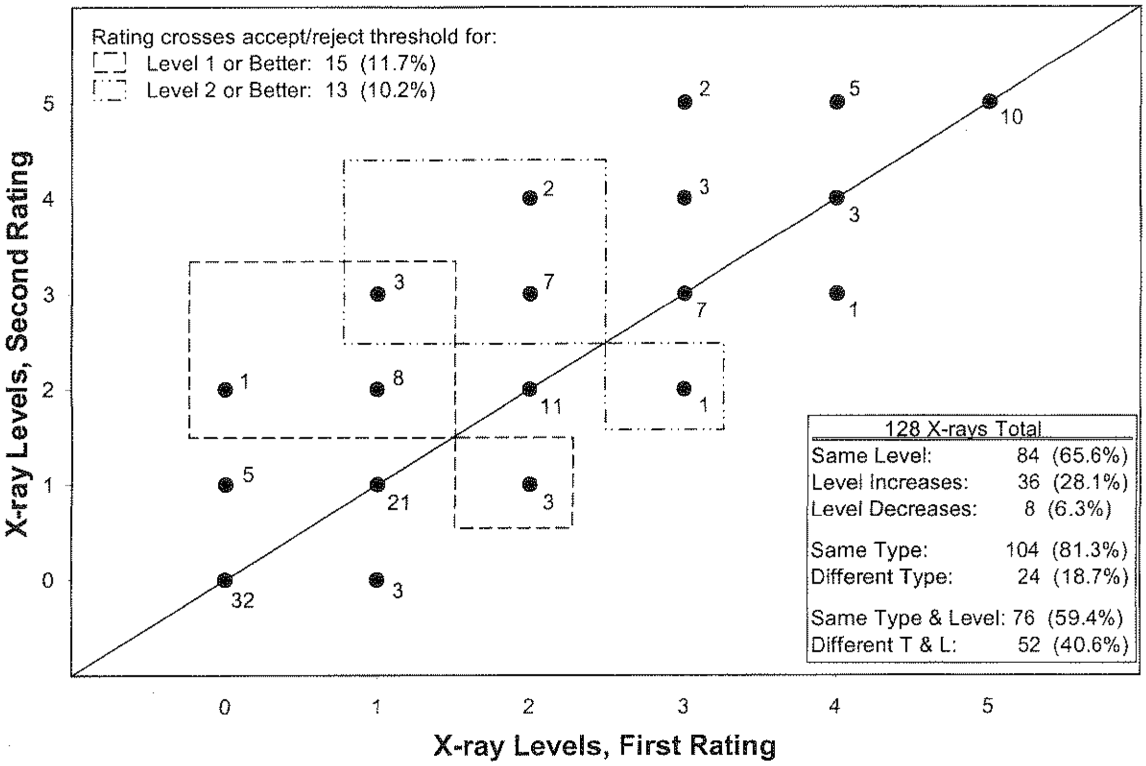

Fig. 3 Comparison between first and second ratings of Radiographer 2

correlations were found, the second part of the study consisted of digitizing three production radiographs to determine if it was possible to correctly assess their x-ray level using the correlations developed from the reference radiographs. Before discussing the development and application of the correlations between defect measurements and ASTM x-ray level, however, it is worthwhile to discuss the procedure used to process the x-rays.

Image processing procedure

The radiographs were scanned using high optical density scanning equipment at the Iowa State University Center

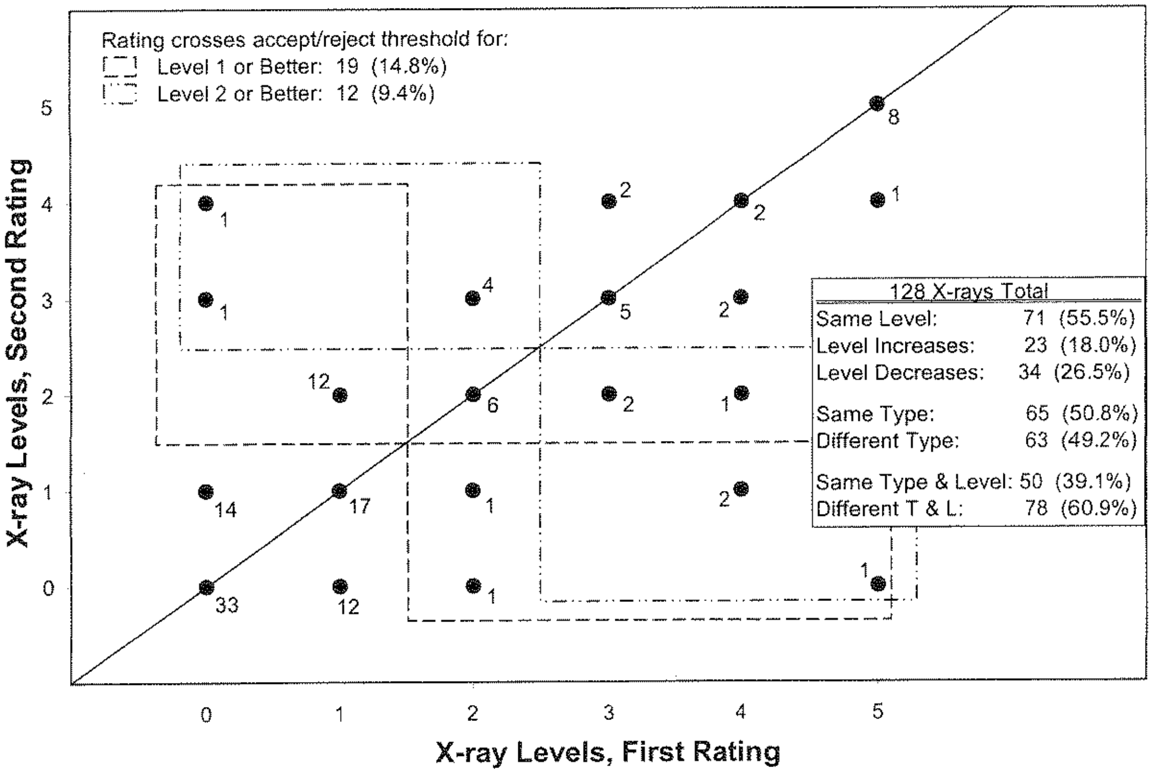

Fig. 4 Comparison between first and second ratings of Radiographer 3

for Nondestructive Evaluation (CNDE). The scanned images were then processed with image analysis software. Scion Image[8] was used first, to remove the differences caused by varying x-ray contrast levels and different exposure times during scanning. The result was then exported into Transform,[9] where the image was smoothed and a cutoff was set to determine which parts of the image were defects and which were background. This resulted in a binary matrix (''0'' = background, ''1'' = defect), which was then saved as a text file. Finally, a FORTRAN program that calculates defect measurements read this text file and computed the desired quantities. Many different defect measurements were investigated in this work. Three of these measures will be discussed here: defect area percentage, defect circumference ratio, and equivalent defect radius.

A detailed outline of the procedures involved in this study is as follows:

1 Scan x-ray
2 In Scion Image:
  a) Set scale: 5.6 pixels/mm was used in this work
  b) Correct images for varying x-ray contrast levels and different exposure times during scanning
    - Subtract background: use the option ''2D Rolling Ball'' with a 10 pixel radius
    - Find the mean optical density of the resulting background (MDB); use the average of several measurements over small areas not containing defects. The optical density of each pixel is simply that pixel's gray scale value, which can range from 0 (white) to 255 (black).
    - Multiply all pixels (background and defects) by 5/MDB
  c) Digitize image: select an area (all or part of the image), and transfer the selection into a matrix containing pixel values
    - Export selection as a data set: *filename.tif*
3 In Transform:
  a) Read *filename.tif*
  b) Smooth image: use smoothing option with 2 sweeps
  c) Define defects: examine each pixel's gray scale value
    - If value ≤ 17.5, set it to 0 (background)
    - If value >17.5, set it to 1 (defect)
  d) Remove obvious non-defects (e.g., edge effect on right edge of the x-ray shown in Fig. 5(a))
  e) Save the result as a matrix in text format: *filename.txt*
4 FORTRAN program:
  a) Read *filename.txt* (binary matrix)
  b) Compute the total area and circumference of defects:
    - Defect area $A_{defects}$ = number of defect pixels (pixels with a value of ''1'')
    - Defect circumference $CF_{defects}$ = number of ''1'' pixels adjacent (up, down, left, right) to at least one ''0'' pixel
    - Total area A_{total} = total number of pixels
  c) Defect area percentage = $A_{defects}/A_{total}$
  d) Defect circumference ratio = $CF_{defects}/\text{sqrt}(A_{total})$
  e) Equivalent defect radius = $2A_{defects}/CF_{defects}$

The multiplication factor 5/MDB in Scion Image and the cutoff value 17.5 in Transform were selected after considerable trial-and-error. The procedures performed in Scion Image serve to correct for differences in contrast levels between x-rays and even within a single x-ray. The value of 5/MDB worked very well for contrast correction. This can be seen by comparing Fig. 5(a) and 5(b), which show a scanned x-ray before and after Scion Image processing. Notice that the defects visible in Fig. 5(a) also show up well in Fig. 5(b), despite the variance in contrast in Fig. 5(a). Fig. 5(b) also shows that the transition from defect to background is more gradual than sudden. Thus, edge detection must be performed to define where the defect stops and the background begins. An example of edge detection is shown in Fig. 5(c). The top portion of Fig. 5(c) shows a section of the radiograph after step 3(b). Along the dashed line, the optical density (i.e. darkness) values were extracted. These values are shown in the lower portion of Fig. 5(c). The cutoff value 17.5 is shown in the optical density plot, denoting the boundary between defects and background. The binary image that results from this cutoff operation is shown in Fig. 5(d). The combination of the values 5/MDB and 17.5 was found to give the best digital representation of the defects seen in the radiographs. These constants are highly dependent upon each other. Fig. 5 shows that the image processing algorithms listed in steps 2 and 3 result in binary digital images that capture the defects on the scanned x-rays quite well.

One might question the use of the single cutoff value 17.5 for all x-rays, whether they have minor or severe shrinkage indications. It seems plausible that severe shrinkage defects may be larger than minor defects, which would lead to a higher optical density in the severe defects. If this were the case, minor defects could have a low enough optical density that they would be mistaken for background by the above procedure. Optical density was, in fact, one of the defect measurements originally investigated in this work. However, it was determined that the mean optical density of defects does not correlate with ASTM x-ray level. Furthermore, the results of the study of equivalent defect radius versus x-ray level (which will be discussed later) show that the average size of defects does not change significantly with x-ray level. This indicates that the optical density of defects is about the same for all x-ray levels, which implies that the use of a single cutoff value is valid.

As a final note on the procedure, the use of two software packages and a separate FORTRAN program is probably not necessary to achieve the desired result. The procedure listed here evolved as the project unfolded,

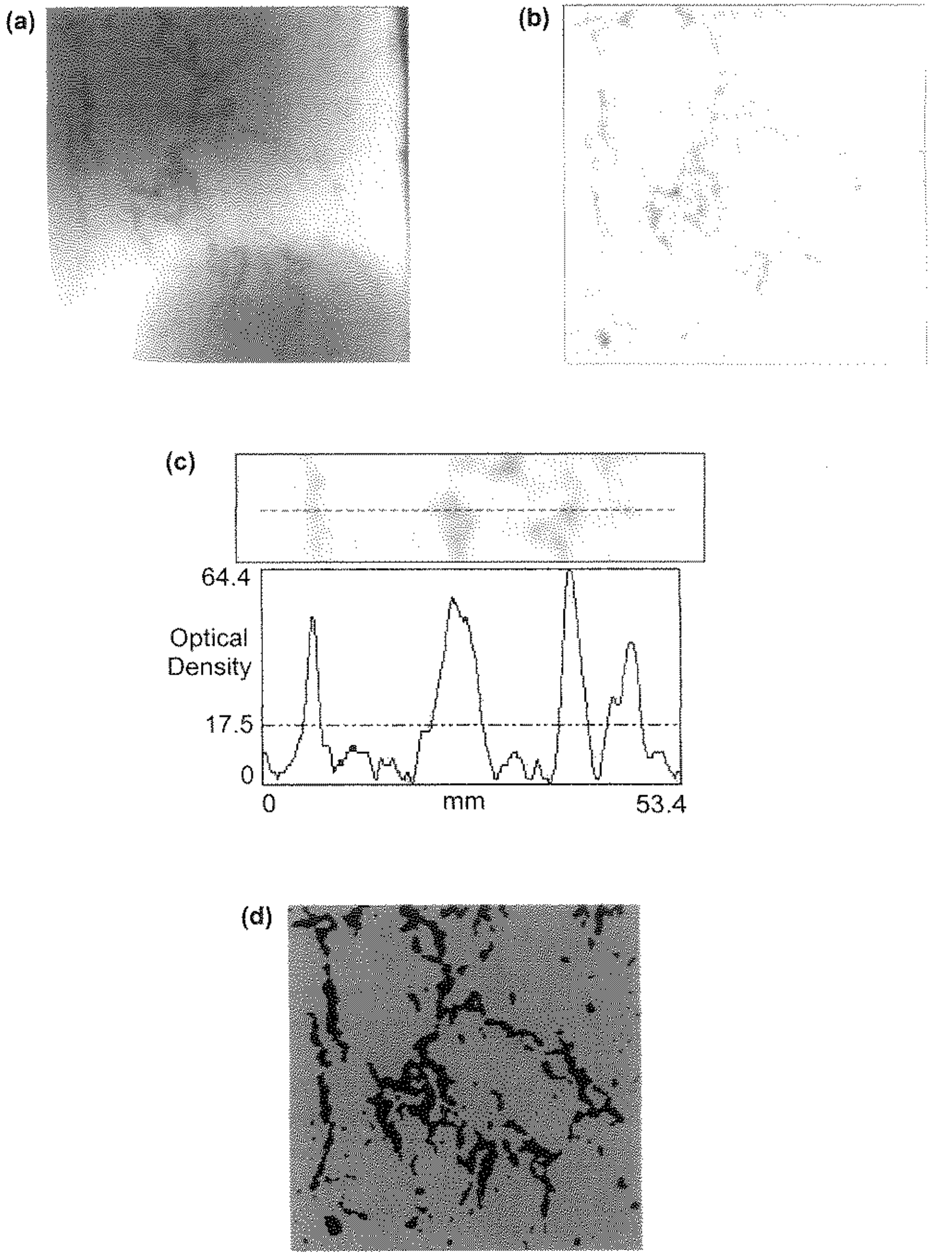

Fig. 5 Reference radiograph CB-5 (a) after scanning, (b) after Scion Image processing, and (d) after Transform processing. (c) shows the optical density profile along a line, and shows the cutoff value of 17.5 used to differentiate defects from background

and once a working procedure was established, it was utilized thereafter. A procedure that produces results similar to those shown in this work could probably be developed for a single image analysis package (Scion Image, Transform or another package). The smoothing and background subtraction operations are common features in such packages, although they use different techniques that can lead to different results. As with the procedure listed here, it would require a significant amount of trial-and-error to produce the desired image. This is the reason no attempt was made to simplify the current procedure once it was developed. With respect to defect measurements, both Scion Image and Transform allow the user to employ macros, which could replace the FORTRAN program.

Processing of reference radiographs

For the first part of this study, the procedure described in the previous section was performed on ASTM E186 reference radiographs for shrinkage defect classes CA, CB and CC, Levels 1–5 each. To determine the effects of different scanning exposure times, three of the reference radiographs (CB1, CB2 and CB4) were scanned twice, using different exposure times for each scan to produce different levels of contrast. In addition, the area of significant defects in CB5 was larger than the scanner area, so three different areas of CB5 were scanned to cover the entire image. In the defect measurement plots in this section, if a single value is shown for a reference radiograph that was scanned more than once, this value represents the average value from the two or three scans

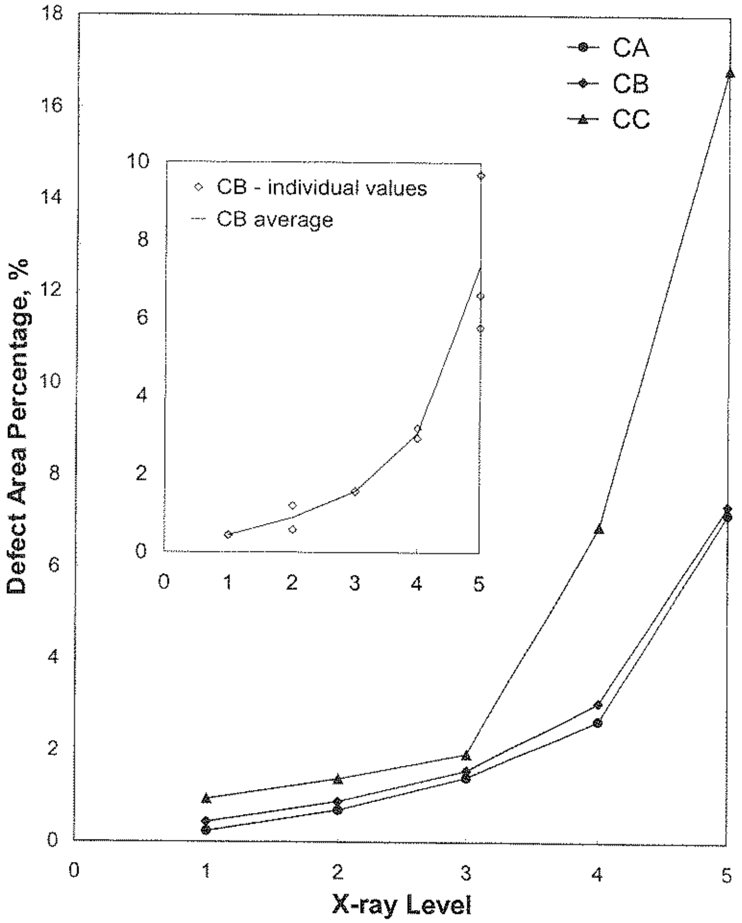

Fig. 6 Defect area percentages of ASTM standard E186 reference radiographs for shrinkage defect classes CA, CB and CC. Insert plot shows individual CB values used to determine the average CB curve used in main plot

of that x-ray. The values of the individual scans will also be shown where applicable.

The resulting defect area percentages and defect circumference ratios for the E186 reference radiographs are plotted against x-ray level in Figs. 6 and 7, respectively. The insert plots in these two figures show individual values for the multiple scans of reference radiographs CB1, CB2, CB4 and CB5 mentioned in the previous paragraph, along with the line passing through the average values. In both Figs. 6 and 7, the individual values for CB1 and CB4 are very close to each other. This indicates that the difference in exposure time (and hence contrast) between the two scans of these radiographs was well accounted for by the Scion Image procedure. However, the two values for CB2 in Figs. 6 and 7 exhibit more scatter, which is disappointing. For CB5, one of the three scans has defect area and circumference values that are significantly higher than the other two, indicating that there were more defects in that scan area than in the other two. The average value, in this instance, is probably a good representation of the entire radiograph.

Fig. 6 shows that the defect area percentages for classes CA and CB are very similar for all five x-ray levels. This is not surprising, considering the similar veinous nature of both of these defect classes (recall that CA is individual veinous strands of defects, while CB is grouped veinous strands). Class CC (spongy defects) has values close to those of CA and CB for Levels 1–3, but then the CC values become much larger than those of the other classes for Levels 4 and 5. Notice that, for a given x-ray level, the area percentages increase with defect class (CA < CB < CC). When the nature of the three defect classes is taken into account, this seems reasonable. Also, for a given shrinkage class, the defect area percentage increases with x-ray level. This is promising, as it indicates it may be possible to determine a x-ray level from the defect area percentage of an x-ray with a known shrinkage class. However, Fig. 6 points out a rather disappointing aspect of the defect area percentage measurements: to use these curves to determine x-ray level, one must know (i.e., subjectively determine) the shrinkage class. It was hoped that, for example, the area percentages for classes CA, CB and CC for a Level 2 x-ray would all be smaller than all area percentages for Level 3, and larger than all area percentages for Level 1. If this were the case, definition of defect type would be unnecessary, and the level could be determined outright. But the only place this clearly occurs is between Levels 3 and 4. There is a small gap between the values for Levels 4 and 5, but the CC4 area percentage is close to the CA5 value.

Fig. 7 shows that the same trends seen for defect area

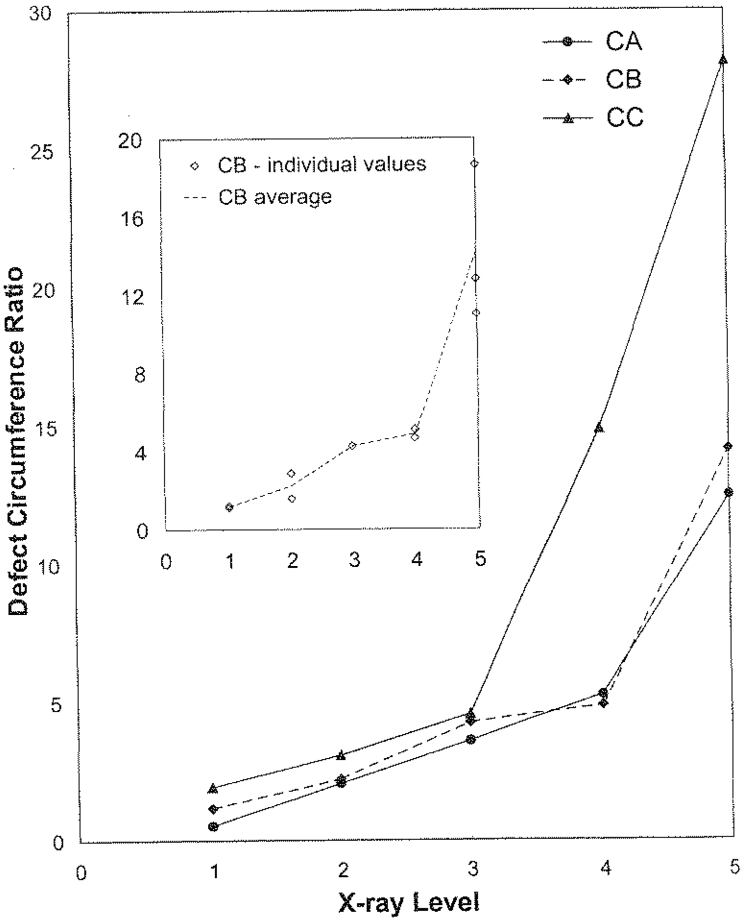

Fig. 7 Defect circumference ratios of ASTM standard E186 reference radiographs for shrinkage defect classes CA, CB and CC. Insert plot shows individual CB values used to determine the average CB curve used in main plot

percentage are evident for the defect circumference ratio as well. The defect circumference ratio increases with x-ray level for each shrinkage class, and for a given level the circumference generally increases with shrinkage class. As with defect area percentage, the defect circumference ratio may be useful in determining x-ray level if the shrinkage class is known, but the level cannot be determined without this information. Finally, Figs. 6 and 7 both illustrate that shrinkage x-ray levels do not seem to vary in a linear fashion over all five x-ray levels. The trend lines in Figs. 6 and 7 for class CA and CB defects show that the quantity of defects increases in a somewhat mild, steady fashion between Levels 1 and 4, and then increases sharply between Levels 4 and 5. For class CC defects, there is a steady increase between Levels 1 and 3, then a sharp increase between Levels 3 and 5.

Fig. 8 shows the equivalent defect radius for Levels 1–5 of all three defect classes. If one assumes the defects on the x-rays are all circles of the same size, the equivalent defect radius is simply the radius of these circles. Class CA, CB and CC defects are obviously not circular, but the equivalent defect radius still provides insight into the size of the defects, and the relative changes in size with x-ray level. Fig. 8 demonstrates that, while there is some increase in defect size from X-ray Level 1 to 5, it is not a large increase. It is also evident that the size does not increase with every level, since the equivalent defect radius decreases for some levels. Because the average defect size does not significantly increase with x-ray level, it can be concluded that increases in shrinkage severity are mainly due to an increase in the number of defects, rather than the size. The range of the equivalent defect radii shown in Fig. 8 is about 0.6–1.1 mm. Multiplying this value by two to compute an equivalent diameter, the size of class CA, CB and CC defects for all x-ray levels is on the order of one to two millimeters.

It is noteworthy that the relatively constant size of shrinkage defects over all x-ray levels indicates that defect optical density measurements would not be useful for determining x-ray level. If it was determined that the size of defects increased with x-ray level, then the optical density of the defects would increase as well. However, since the defect size does not increase appreciably, the optical density of defects would not significantly change either. It is stated in the ASTM x-ray rating standards (ASTM E186, E446 and E280) that radiographic defect density compared to background density should not be used to determine x-ray level, because this variable is highly dependent on "technical factors." From this work, it appears that relative defect density would not be a good measure of x-ray level in any case.

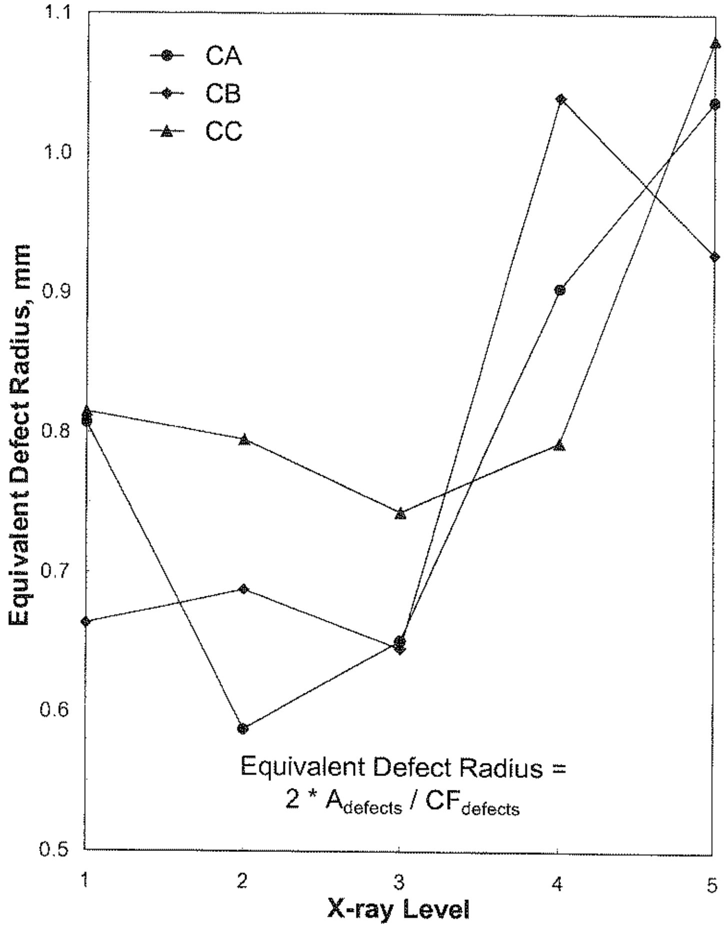

Fig. 8 Variation of equivalent defect radius with x-ray level for class CA, CB and CC shrinkage defects

Quantitative determination of X-ray level for production radiographs

Once the correlations shown in Figs. 6 and 7 were established, the ability to determine ASTM shrinkage x-ray level using these relationships was tested. As indicated in the previous subsection, it was determined that these correlations could not be used to determine x-ray level without knowledge of shrinkage type. So three production radiographs with known shrinkage type ratings from the first SFSA/University of Iowa steel plate casting trials[5,6] were selected for this part of the study. Because these radiographs were used in the repeatability and reproducibility study detailed earlier in this paper, there were seven different x-ray ratings for each one. The individual ratings, mean x-ray levels and 95% confidence intervals for the three trial cases are listed in Table 3. The radiographs were scanned at the Iowa State University CNDE, and then processed using the Scion Image and Transform procedures listed earlier.

The processed images for Trial Case 3 are shown in Fig. 9, which shows several alternate selection areas (Fig. 9(c)) in addition to the complete processed image of the x-ray (Fig. 9(b)). For each trial case, several selection areas were analyzed to determine the impact of the choice of this area on the resulting x-ray rating. The area A_{total} is included in the defect area and circumference measurement variables to accommodate the prorating requirement in the ASTM x-ray rating standards (ASTM E186, E446 and E280). These standards state that the ''area of interest'' on a production radiograph should be prorated to the size of the applicable reference radiograph. By forming the ratios $A_{defects}/A_{total}$ and $CF_{defects}/\text{sqrt}(A_{total})$, this prorating is done automatically. But what exactly is the ''area of interest''? It obviously needs to include the defects of interest, but how much

Table 3 X-ray ratings for the three trial cases investigated

Trial Case	Rating 1	Rating 2	Rating 3	Rating 4	Rating 5	Rating 6	Rating 7	Other Defects	Mean X-ray	1-sided 95% CI
1	0	CA1	CB2	CA1	CA2	CA1	CA1	A1, B2	1.14	1.69
2	CB2	CB4	CB5	CC2	CB2	CA3	CB3	B2	3.00	2.83
3	CB5	CB5	CB5	CB5	CB5	CA5	CA5	none	5.00	0.00

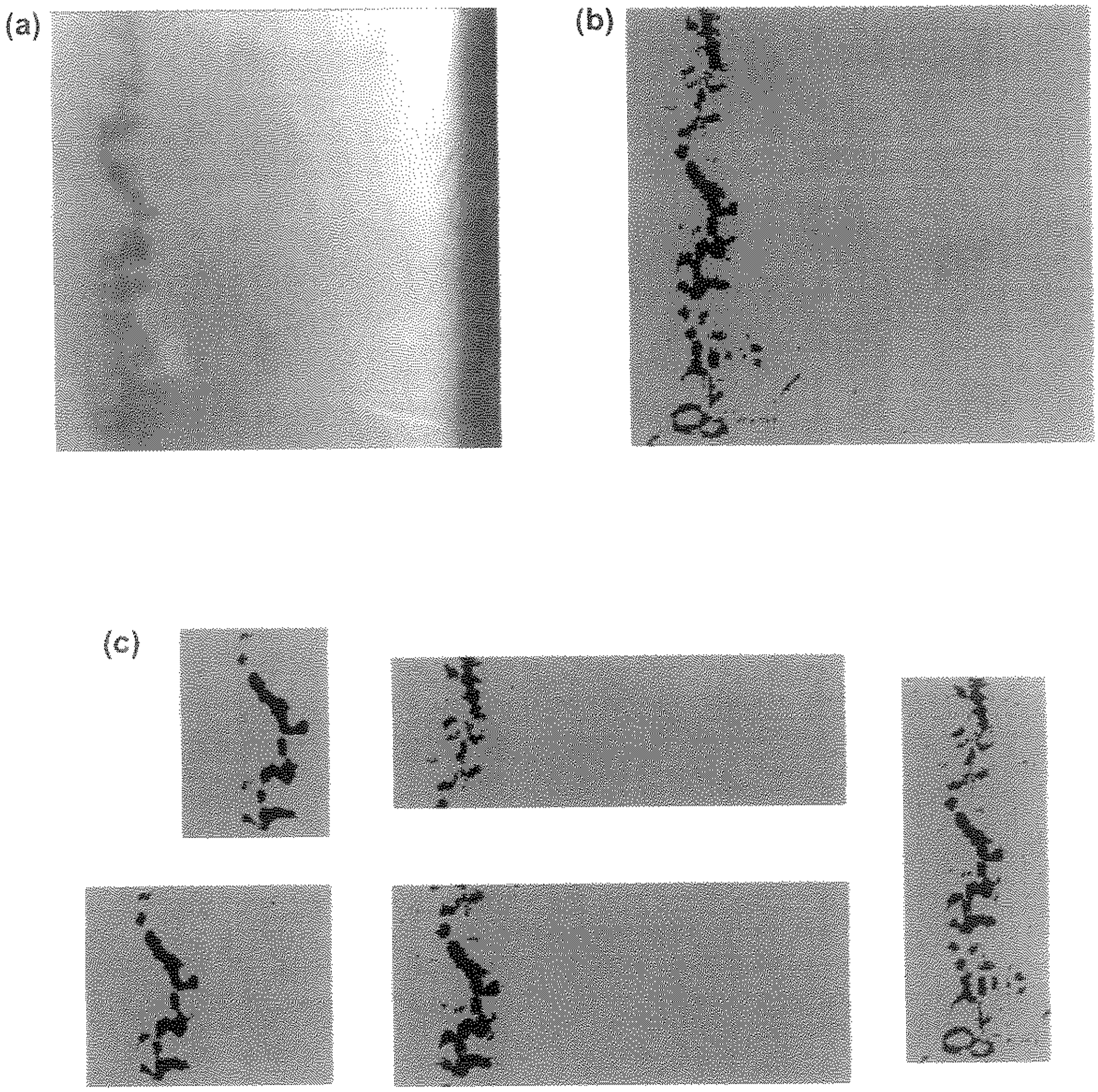

Fig. 9 Trial Case 3 (X-ray Level 5) (a) after scanning, (b) after Transform processing, and (c) several alternate selection areas

sound area around the defects should be included? This is a very important consideration for radiographs displaying concentrated defect patterns, such as the centerline shrinkage shown in Fig. 9. By computing the x-ray level for several choices of selection area, it will become evident how important this choice is.

The defect area percentage and defect circumference ratio were calculated for all of the selection areas for Trial Cases 1, 2 and 3. The defect area percentages for all selection areas were then plotted along the trend line shown in Fig. 6 that correlates the defect area percentage of the class CB reference radiographs to their x-ray level. This resulted in Fig. 10, which displays the desired relationship between the defect area percentages of the trial case selection areas and ASTM x-ray level. An analogous procedure was performed for the defect circumference ratios and the class CB trend line shown in Fig. 7, and the resulting plot is given in Fig. 11. In Figs. 10 and 11, the individual selection areas for each trial case are represented by hollow symbols. The filled symbols indicate the mean value of all the selection areas for each trial case. The error bars for the filled symbols correspond to a 95% confidence interval.

As shown in Table 3, Trial Cases 2 and 3 were predominantly assigned type CB shrinkage, and Trial Case 1 was predominantly CA. For simplicity, all three trial cases were compared to the CB reference radiograph trend line. This was considered acceptable because Trial Case 1 is a nearly sound x-ray, and there is very little difference between CA and CB shrinkage at X-ray Level 1. This is evidenced by the similarity in the CA1 and CB1 values in Figs. 6 and 7. Using the CA1 value instead of the CB1 value in Figs. 10 and 11 would not change the resulting x-ray level for Trial Case 1. Furthermore, Trial Case 1 was given a CB rating by one radiographer.

Figs. 10 and 11 show that all the Trial Case 1 selection areas yield very similar values. All of the selection areas have defect area percentages and defect circumference ratios that are below the corresponding values for X-ray Level 1. The ASTM x-ray rating standards state that one should assign an x-ray level by rounding up to the

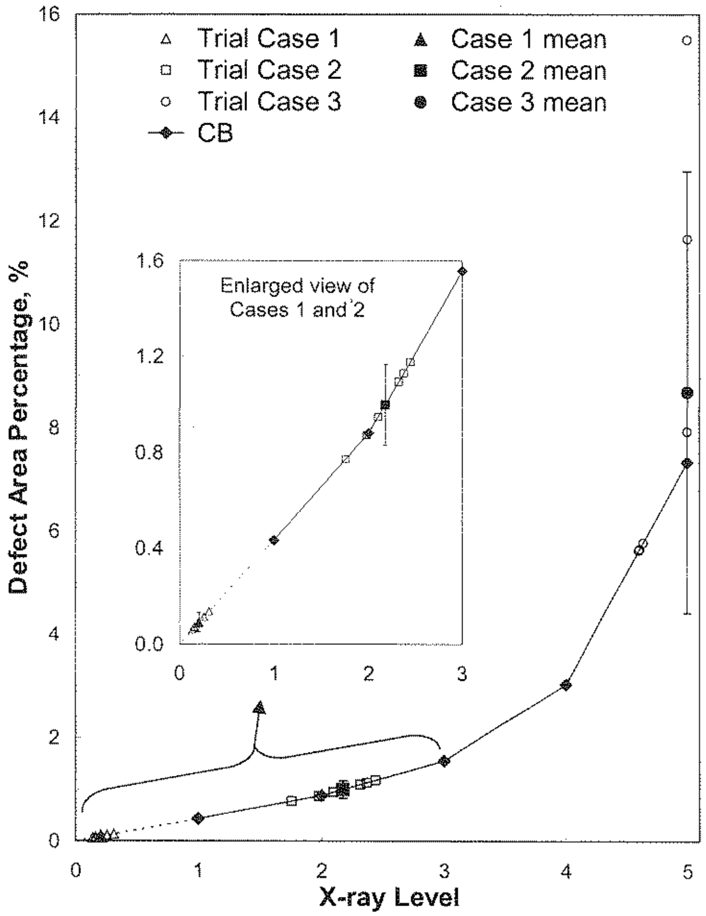

Fig. 10 Defect area percentage of trial cases plotted along the defect area percentage versus x-ray level curve for ASTM standard E186 reference radiographs for CB-type shrinkage. Values shown are for each selection area (hollow symbols), as well as the mean value of all selection areas for each trial case (solid symbols). The error bars on the mean values are 95% confidence intervals. Trial Cases 1, 2 and 3 are X-ray Levels 1, 3 and 5, respectively

next shrinkage severity level greater than that of the production x-ray. Therefore, both figures indicate that Trial Case 1 is X-ray Level 1. This agrees with the mean level of 1.1 assigned to this x-ray. For Trial Case 2, Fig. 11 shows that all of the selection areas give defect circumference ratios between the Level 1 and Level 2 values, indicating that this x-ray is Level 2. However, the defect area percentages shown in Fig. 10 for Trial Case 2 fall both above and below the Level 2 value. The two selection areas below the Level 2 value would indicate that Trial Case 2 is Level 2, and the remaining four areas would indicate Level 3. Viewing the results for Trial Case 2 in both Figs. 10 and 11, a case can be made that this x-ray is either Level 2 or Level 3. The conservative approach would be to use Level 3. The mean level for this x-ray is 3.0, but there is considerable variability in the individual ratings (see Table 3). So neither a Level 2 nor a Level 3 rating would be unreasonable. For Trial Case 3, some of the defect area percentages in Fig. 10 are below the Level 5 reference value, and some are above. By ASTM standards, all of these would indicate that Trial Case 3 is Level 5. The agreement on x-ray level is not quite unanimous in Fig. 11. There is one defect circumference ratio that falls below the Level 4 reference value. In fact, it is just below the Level 3 value (see the hollow circle on the left side of the Level 3 reference diamond in Fig. 11). This circle corresponds to the lower-leftmost selection area shown in Fig. 9(c). Only part of the centerline shrinkage is contained in this area, and it is mostly one connected defect. Thus, the defect circumference in this selection area is smaller than in the other areas chosen. But it is clear from the defect circumference ratios of the remaining selection areas, and from the defect area percentage results, that Trial Case 3 is indeed Level 5. This agrees with the mean level of 5.0.

The analysis of the three trial cases presented here demonstrates that a quantitative determination of ASTM x-ray shrinkage level may be possible, provided that the shrinkage type is correctly determined. From the examples shown here, it is evident that the choice of selection area can be very important. The use of multiple selection areas in this study provided additional data points to help determine the level. Based on these results, it seems that both the defect area percentage and defect circumference ratio should be considered when assigning an x-ray level to a radiograph. It must be re-emphasized that the correct selection of shrinkage

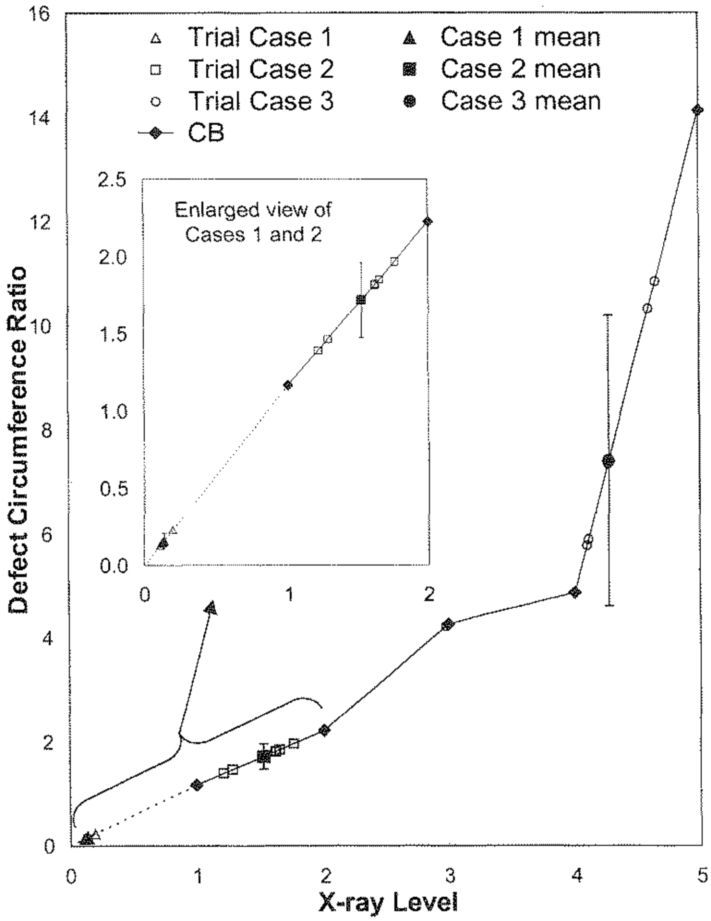

Fig. 11 Defect circumference ratio of trial cases plotted along the defect area percentage versus x-ray level curve for ASTM standard E186 reference radiographs for CB-type shrinkage. Values shown are for each selection area (hollow symbols), as well as the mean value of all selection areas for each trial case (solid symbols). The error bars on the mean values are 95% confidence intervals. Trial Cases 1, 2 and 3 are X-ray Levels 1, 3 and 5, respectively

defect class (CA, CB, CC) is critical for this type of x-ray analysis, since different classes have different reference values used to determine x-ray level. Finally, it seems that the same type of quantitative analysis could also be performed for Category A (gas porosity) and B (inclusion) defects, due to the similar nature of their current rating structures.

Summary and conclusions

Two different studies were presented in this paper that examined the ASTM x-ray shrinkage rating system for radiographs of steel castings. The first study evaluated the repeatability and reproducibility of x-ray shrinkage ratings through a statistical study. The second study involved an effort to determine the shrinkage severity level of x-rays through digital analysis of scanned radiographs.

The repeatability and reproducibility of ASTM shrinkage x-ray ratings was investigated in a statistical study performed on 128 x-rays, each of which were rated seven different times. It was found that the seven ratings were in unanimous agreement on shrinkage type for 37% of the x-rays, on shrinkage level for 17% of the x-rays, and on both type and level for 12.5% of the x-rays. The x-rays that had unanimous agreement on both type and level were all either completely sound, or very unsound (Level 5). By computing a 95% confidence interval for the seven shrinkage level ratings for each x-ray, it was found that x-rays with an average level around 2 or 3 had the largest variability in level ratings, with an average variability of about ±2. The different level ratings for each x-ray were then examined to determine how many x-rays had level ratings both above and below common accept/reject thresholds. 21–35% of the x-rays had ratings that crossed different thresholds, indicating that the castings associated with these x-rays would have been accepted by some radiographers and rejected by others. Two of the radiographers involved in this study rated all the x-rays twice, and analysis was performed to determine the consistency of their ratings. Comparing each radiographer's second rating to their first, both radiographers gave different type ratings for at least 19% of the x-rays and different level ratings for at least 34% of the x-rays. Both radiographers also reversed accept/reject decisions for 10–15% of the x-rays. The results of this statistical study indicate the subjective nature of the x-ray rating procedure.

Next, a study was performed in an attempt to quantify

ASTM shrinkage x-ray rating. ASTM E186 reference radiographs for shrinkage classes CA, CB and CC were scanned and digitized, and measurements of the defects were performed. It was found that the defect area percentage and defect circumference ratio both increased with x-ray level for a given defect class. Also, for a given x-ray level, these measures generally increased with defect class (CA < CB < CC). The increase of defect area and circumference with x-ray level for a given defect class indicates the possibility of determining x-ray level with these measures. However, it was determined that these defect measurements could not be used to determine x-ray level unless the shrinkage type was known. This study also indicated that defect size does not increase considerably with x-ray level. Rather, severity increases due to an increase in the number of defects. The defect size for all three shrinkage classes studied is on the order of one to two millimeters. Once the reference radiographs had been thoroughly analyzed, three production x-rays were digitized. Defect area percentages and defect circumference ratios were computed for various selection areas of each x-ray. By comparing these values to the corresponding class CB shrinkage reference radiograph values, it was possible to correctly determine the x-ray level. It was found, however, that different selection areas could change the resulting x-ray level. Use of multiple selection areas and both the defect area and circumference measures resulted in reasonable x-ray levels. The results of this study indicate that, through digital x-ray analysis, it is possible to reduce the uncertainty in ASTM shrinkage x-ray level rating. However, this digital analysis cannot be done until the correct shrinkage type rating is assigned to an x-ray.

Acknowledgements

This work was supported by the United States Department of Energy through the Cast Metals Coalition (CMC) and the Steel Founders' Society of America (SFSA). Furthermore, we are indebted to Malcolm Blair and Raymond Monroe of the SFSA, for their work in helping organize the casting trials and recruiting members to participate. We would also like to express our gratitude to Joe Gray from the Iowa State University Center for Nondestructive Evaluation (CNDE) for his assistance with the digital x-ray study, and to the radiographers who rated the casting trial radiographs to provide us with the necessary data to perform the statistical study of x-ray ratings. Most importantly, we thank the participants in the plate casting trials for their substantial time and resource investment in all aspects of the Yield Improvement Program. This work could not have been accomplished without their shared efforts. This work was prepared with the support of the U.S. Department of Energy (DOE) Award No. DE-FC07-98ID13691. However, any opinions, findings, conclusions, or recommendations expressed herein are those of the authors, and do not necessarily reflect the views of the DOE.

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(Received 02 January 2001; accepted 24 March 2001)