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A New Standard for Radiographic Acceptance Criteria for Steel Castings

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ABSTRACT

A new standard for the evaluation of steel casting radiographs is proposed to address the shortcomings of current standards such as ASTM E1316-05. Current standards are workmanship standards and are subjective. They also suffer from poor reproducibility. The draft standard presented here uses an acceptance criteria determined from the fractional total length of radiographic indications along a line oriented in a specified direction of interest. This evaluation method and the proposed acceptance criteria can be related to part performance, since the fractional length is referenced to a prescribed feature length. Designers can select this feature length to ensure that castings meeting the acceptance criteria will also meet their designed performance requirement. Example evaluations of radiographs are presented, and methods are demonstrated to relate these evaluations to part performance. These examples show that the relationship between the radiographic evaluation and part performance can be conservative or non-conservative according to the designer's prescription. The proposed standard is applied to the ASTM E186 standard radiographs and the results demonstrate the subjectivity of this current standard.

INTRODUCTION

All components have performance limitations. These limitations are due to part design, part misuse, manufacturing practices and material characteristics. Non-destructive examination is specified by designers and users to ensure that the component purchased does not have features that would limit the component performance to less than the design requirement. Radiography can be used to detect internal features in castings. The features may have a higher or a lower density than the parent metal. These internal features are not necessarily the result of poor process control or defective material. Features detected by radiography may be rectified through further processing if the purchase requirement acceptance criteria would reject the component. Only when the component does not meet the purchase requirement when finished do the features that cause the nonconformance become defects (ASTM E1316-05).

A new standard is proposed for the evaluation of radiographs of steel castings. This standard allows the designer and user to specify acceptance criterion(ia). The acceptance criterion(ia) have been developed to allow radiographic testing to be useful in assessing component performance. Selecting the appropriate acceptance criterion(ia) is the responsibility of the purchaser. The manufacturer's responsibility is to produce and inspect the component in accordance with the purchase specification requirements and to certify that it meets the acceptance criterion(ia) imposed.

Historically, radiographic testing has been based on a subjective comparison of the part radiograph with reference radiographs. This method disallows the use of greyness levels. It may also require the evaluator to prorate the radiograph of the area of interest of a part to the reference radiographs. The reference radiographs are assigned levels, but there is significant similarity in the levels causing problems in interpretation.[1] The reference radiographs are workmanship standards and are unrelated to performance. The inability to reproducibly determine the radiographic quality level of a component[1] and the inability to relate that level to performance in a satisfactory way has been the impetus behind the development of this standard.

This draft standard uses a fractional length as the acceptance criterion(ia). The total length of the radiographic indications (l_i) is measured in a specified area of interest along a straight line that is oriented in a specified direction of interest. The maximum total indication length (l_{im}) for any such straight line is determined and then divided by some feature length (L_f) of the casting. This fraction (l_{im}/L_f) is the basis for the levels of acceptance in the standard. By relating the radiographic indication length to the feature length, a designer can use the standard to ensure the indications present on the radiographic film will not limit the component performance to less than the design requirement.

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PROPOSED NEW STANDARD FOR RADIOGRAPHIC ACCEPTANCE CRITERIA

1. SCOPE

1.1 This specification covers acceptance criteria for the volumetric inspection of steel castings when nondestructively examined by radiographic inspection.

1.2 This specification is to be used whenever the enquiry, contract, order, or specification states that the acceptance standards for radiographic inspection shall be in accordance with (XXXX? This standard's number)

2. REFERENCE DOCUMENTS

2.1 ASTM Standards:

3. TERMINOLOGY

3.1 Definitions:

3.1.1 Crack – an indication on a radiographic film with a length that exceeds 10 times the width.

3.1.2 Area of interest – the area of the casting required to be radiographed and evaluated.

3.1.3 Direction of interest – the orientation on the casting specified by the purchaser for the measurement of the indication length. For example, the direction of interest might be perpendicular to the principal load in a cast bar. If the bar were loaded in tension axially the direction of interest would be perpendicular or across the bar.

3.1.4 Indication length (l_i) – a measured length of an indication on a radiographic film in the direction of interest.

3.1.5 Feature length (L_f) – a length value given in the purchase requirements used to assess the indication length.

3.1.6 Relevant indication – only an indication length that exceeds 1/16th in (1.6 mm) is considered relevant.

4. ORDERING INFORMATION

4.1 The inquiry and order should indicate the following information:

4.1.1 Radiographic practice – unless a specific radiographic practice is specified, the method used is determined by the manufacturer.

4.1.2 Area of interest.

4.1.3 Direction of interest.

4.1.4 Feature length for evaluation (L_f).

4.1.5 Acceptance level.

5. PERSONNEL QUALIFICATIONS

5.1 Personnel performing the examination shall be qualified in accordance with an acceptable written procedure as agreed upon between the purchaser and manufacturer.

6. EVALUATION OF INDICATIONS

6.1 All relevant indications present on radiographic films shall be evaluated in terms of the acceptance criteria.

6.2 The length (l_i) of each indication within the area of interest, along a continuous straight line oriented in the direction of interest, is measured. If the distance between two indication lengths is smaller than the length of the smaller indication, the two indications, together with the space between the indications, are treated as a single indication. The total indication length is obtained as the sum of all indication lengths on the straight line. The maximum total indication length (l_{im}) on any such single straight line is used to assess acceptance of the area of the casting being evaluated. This maximum total indication length (l_{im}) is divided by the specified feature length (L_f) to calculate the maximum indication fraction F ($F = l_{im} / L_f$).

7. ACCEPTANCE CRITERIA

7.1 Cracks are unacceptable.

7.2 Maximum indication fractions exceeding the limit in Table 1 for a specified acceptance level are unacceptable.

Table 1. Acceptance Criteria Maximum Indication Fraction Limits.

Acceptance Level	Level I	Level II	Level III	Level IV	Level V
F Limit	$F = 0.1$	$F = 0.2$	$F = 0.3$	$F = 0.4$	$F = 0.5$

7.3 In the case of a quality check after the casting has been certified, the acceptable total indication length (l_{im}) for the levels of Table 1 will be increased by 1/16th in (1.6 mm) to account for reproducibility in the evaluation.

8. CERTIFICATION

8.1 The manufacturer shall certify that the inspection was performed in accordance with the appropriate practice and the parts were found to meet the requirements of the specified inspection level of this specification.

SUPPLEMENTARY REQUIREMENTS

The following supplementary requirements shall apply only when specified by the purchaser in the contract or order.

S.1 The purchaser and supplier may agree to a certain maximum indication length instead of selecting a level from Table 1.

S.2 The purchaser and supplier may agree to a certain maximum indication area instead of selecting a level from Table 1. In this case, the purchaser and supplier must agree on a method to measure the area.

COMMENTARY ON DEVELOPMENT AND USE

The radiographic inspection standard proposed here was developed with the intent of allowing purchasers of steel castings to apply acceptance criteria that can, in some instances, be related to mechanical performance of the component. This commentary provides additional guidance to the radiographer and the designer on the use and application of the standard. The relation of the proposed standard to the ASTM E186 reference radiographs is also discussed.

INDICATION EVALUATION

As illustrated in Figures 1 and 2, the area of interest of a casting is evaluated by measuring the total length of all relevant indications, l_i, on the radiographic film(s), along a single straight line that is oriented in the direction of interest. No distinction is made between different types of indications (shrinkage, gas porosity, inclusions, etc.), except that cracks are not included. The area of interest does not need to coincide with the size of a single radiograph; it could be smaller or larger; if it is larger, multiple radiographs must be joined together to cover the entire area of interest. In the example given in Figure 1, note that the specified direction of interest does not match the orientation of the edges of the radiograph. Therefore, the radiograph was oriented such that the direction of interest is in the vertical direction. Then, the straight line can simply be shifted horizontally to keep it oriented in the direction of interest. The straight line was shifted until the maximum value of the total indication length, l_{im}, in the area of interest was obtained. Note that the maximum total indication length would be much larger if, for example, the direction of interest in Figure 1 were horizontal rather than vertical. The measured maximum total indication length, l_{im}, is then divided by the specified feature length, L_f, to calculate the indication fraction, $F = l_{im} / L_f$, that can be limited by the acceptance level chosen. The feature length is not indicated in Figure 1, since it can be any dimension of the casting section, including the thickness.

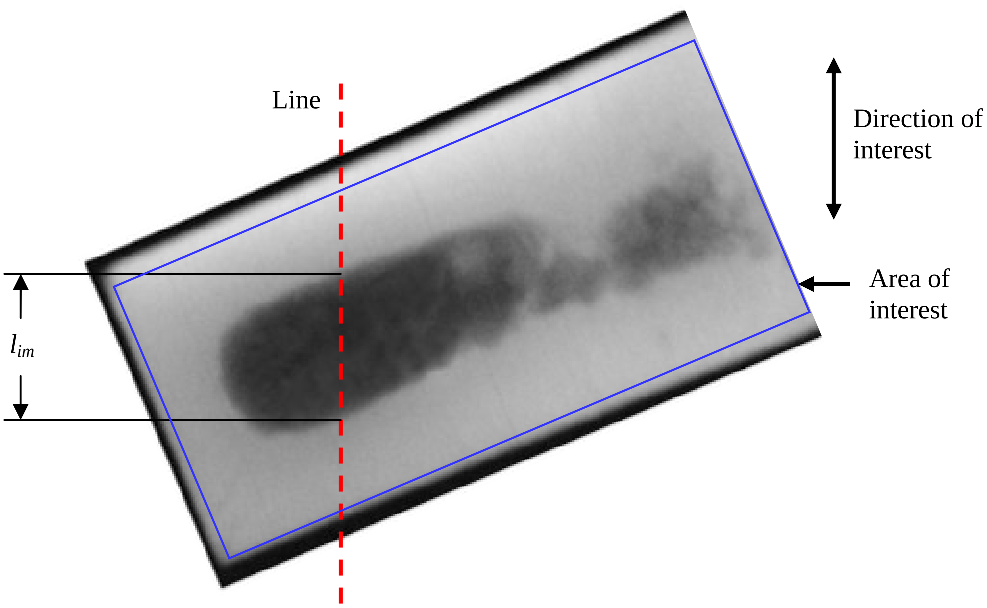

Fig. 1. Example of the measurement of the maximum total indication length, l_{im}, on a radiograph.

If the distance between two indication lengths is smaller than the length of the smaller indication, the two indications, together with the space between the indications, are treated as a single indication. Figure 2 shows examples where the distance between some of the indications along the straight lines shown on the radiograph is so small that they are treated as a single indication. In order to illustrate the importance of the orientation of the lines, Figure 2 shows straight lines for two different directions of interest. In practice, the direction of interest could be included on the radiographic film by placing, for example, a duly oriented lead wire on the casting section to be radiographed.

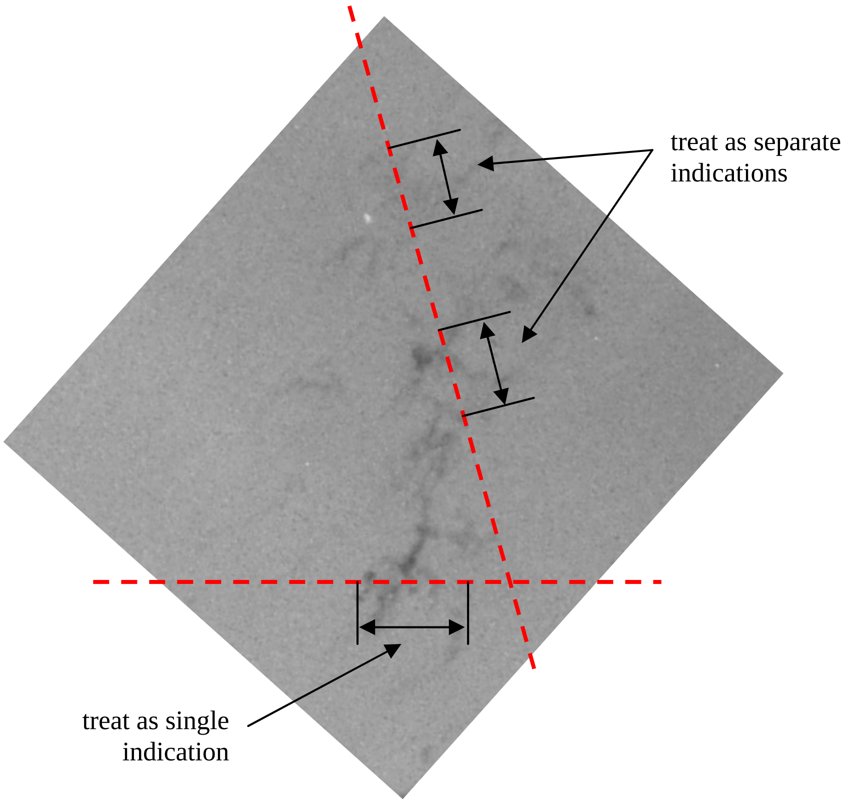

Fig. 2. Example of the measurement of indication lengths for closely spaced indications.

RELATION OF ACCEPTANCE CRITERIA TO MECHANICAL PERFORMANCE

The proposed acceptance criteria, through the maximum indication fraction, F, can be used to obtain an estimate of the effect of the radiographic indications on the stiffness and load-carrying ability of the casting section being evaluated. The radiographic indications, regardless of their nature, are assumed to correspond to voids inside of the casting. These voids reduce the stiffness and load-carrying ability of the casting section. The amount of the reduction is controlled by the maximum lost (to voids) cross-sectional area, A_{im}, in a plane perpendicular to the direction of the loading.[2] Smaller voids present along the loading direction, either in front or behind the plane with the maximum lost cross-sectional area, have no effect on the overall stiffness and load-carrying ability of the section. The maximum indication fraction is then given as the ratio of this maximum void area to the sound cross-sectional area, i.e., $F = A_{im}/A$. Figure 3 shows that the effective stiffness (elastic modulus, E) and load-carrying ability (yield strength, σ_y), normalized by the sound values, decrease linearly with the maximum indication fraction, F. For example, if the maximum lost cross-sectional area is 15% of the total cross-sectional area (F = 0.15), the section would retain 85% of its stiffness and load-carrying ability; according to Table 1, a value of F = 0.15 would correspond to a Level II casting section. Note that the reductions in the mechanical properties shown in Figure 3 are the same for any material, regardless of whether it is ductile or brittle.

Most often, a radiograph is taken such that the direction of the loading is parallel to the film. Thus, to obtain the maximum lost cross-sectional area, A_{im}, in a plane perpendicular to the direction of the loading, it is not sufficient to measure the maximum total indication length, l_{im}, in the direction of interest on the radiograph, but the depth of the voids corresponding to the indications must be known as well. Unfortunately, the greyness levels of the indications on a standard film radiograph cannot easily or at all be used to obtain a measurement of the depth of the voids corresponding to the indications. To overcome this problem, and still obtain an estimate of the fraction of the cross section that is lost to voids, assumptions must be made about the depth of the voids. This is discussed in the following paragraphs.

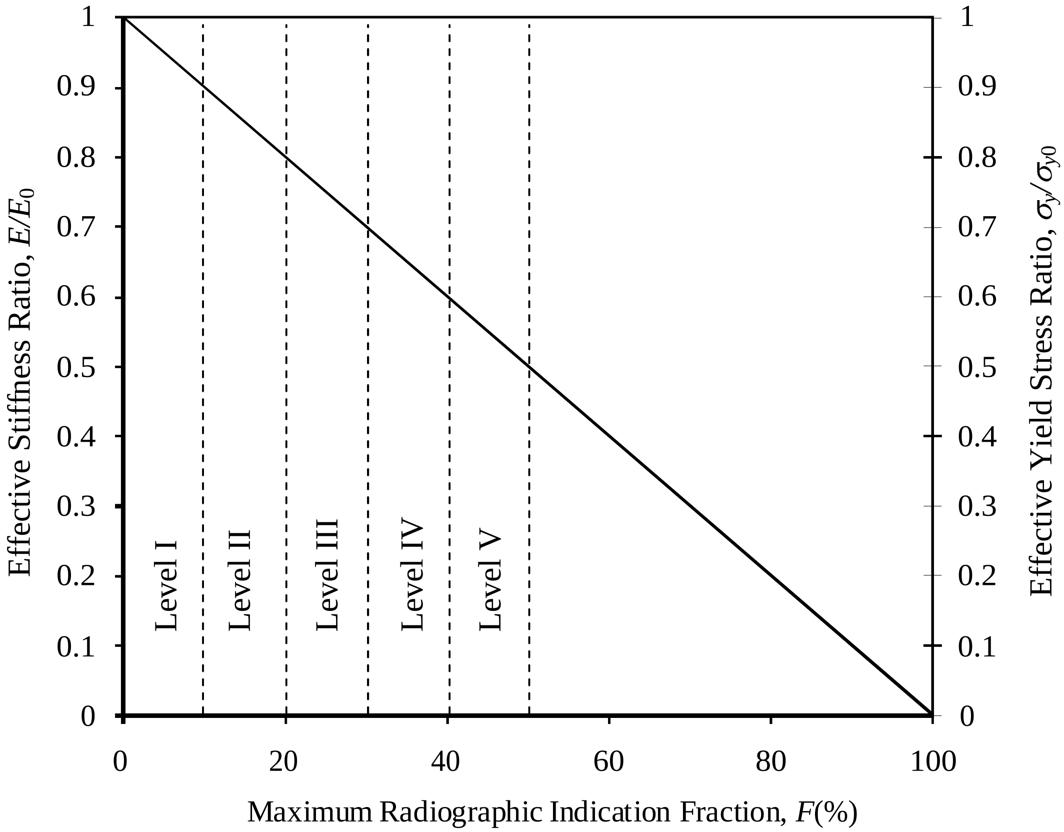

Fig. 3. Relationship between effective mechanical properties and the maximum radiographic indication fraction, F. Properties are normalized with their sound values, E_0 and σ_{y0}.

Consider a plate-like steel casting section of length L = 19", width W = 5.5" and thickness T = 1", as shown in Figure 4(a). The steel is assumed to have an elastic modulus of E_0 = 207 GPa (30,000 ksi) and yield strength of σ_{y0} = 763 MPa (111 ksi). In this finite element analysis of steel with porosity, the effect of porosity was be simulated by locally reducing the elastic modulus depending on the porosity level at the finite element nodes.[2] Here, since there is either 100% sound material or a hole at the nodes, the modulus values are either 207 GPa or ≈ 0 GPa, respectively. The plate is loaded in the axial (length) direction with a uniform nominal tensile stress of 500 MPa (72.5 ksi), as can be seen in Figure 4(b). In Figures 4(c) and 4(e), two porosity distributions are shown that give identical indications on a top radiograph, other than for the greyness levels. In Figure 4(c), the porosity is assumed to be a 0.11" thick layer located at the plate mid-thickness; this value of 0.11" represents a realistic estimate of the maximum depth of centerline shrinkage voids encountered in a plate of 1" thickness when the feeding distance is exceeded. In Figure 4(e), the porosity is assumed to extend through the entire thickness of the plate; this assumption represents a worst case scenario that may be applied by a designer in the absence of any information regarding the void depth. For a direction of interest that is in the width direction, which is perpendicular to the loading direction, the maximum total indication length for both porosity distributions is given by l_{im} = 2.7", as indicated in Figure 4(c). Figure 4(d) shows that for the realistic 0.11" thick porosity layer, the stresses are only slightly enhanced in the solid material adjacent to the voids. On the other hand, for the worst case scenario of the porosity extending through the entire thickness of the plate, Figure 4(f) shows that the local stresses can reach values as high as 1,200 MPa (174 ksi) and that significant yielding occurs. Clearly, the depth of the porosity has a strong effect on the mechanical behaviour of the plate.

Figure 5 shows predicted stress-strain curves for the axially loaded plate of Figure 4. Three curves are shown corresponding to the sound plate [as in Figure 4(a)], the plate with a 0.11" thick layer of porosity at mid-thickness [as in Figure 4(c)], and the plate with the porosity extending through the entire thickness [as in Figure 4(e)]. It can be seen that the thin layer of porosity has a relatively minor effect on the stiffness and load-carrying ability of the plate. Measuring the effective elastic modulus and yield strength from the stress-strain curve in Figure 5, a reduction from the sound values of 5.5% is obtained. On the other hand, for the worst case scenario of the porosity extending through the entire thickness, the stress-strain curve indicates that the effective elastic modulus and yield strength are reduced by 49%; i.e., the plate starts to plastically deform or yield at 374 MPa (54.2 ksi) [with σ_{y0} = 763 MPa (111 ksi)].

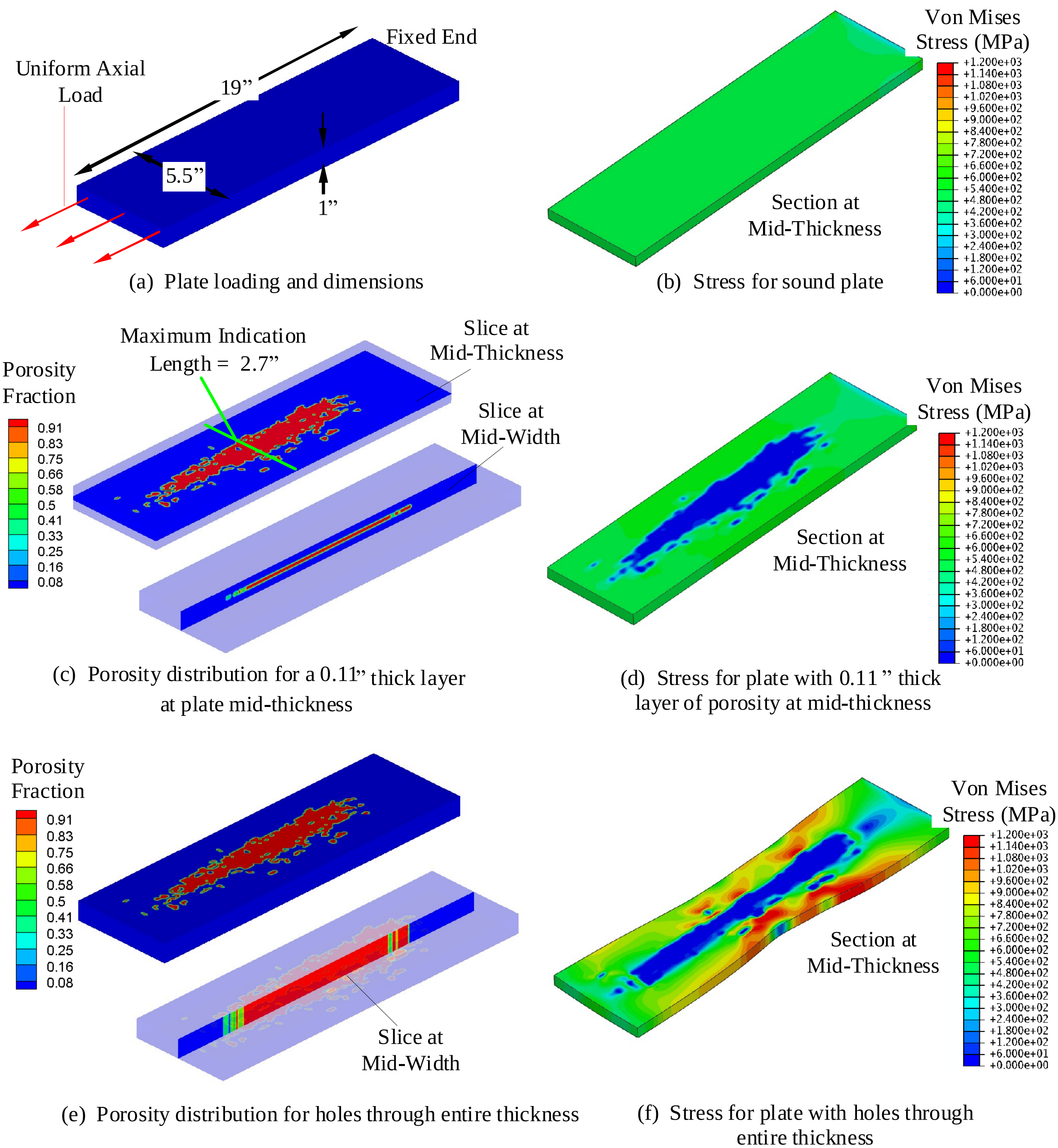

Fig. 4. Effect of porosity depth on the stresses in an axially loaded plate; the porosity distributions shown in (c) and (e) would give the same indications on a top radiograph.

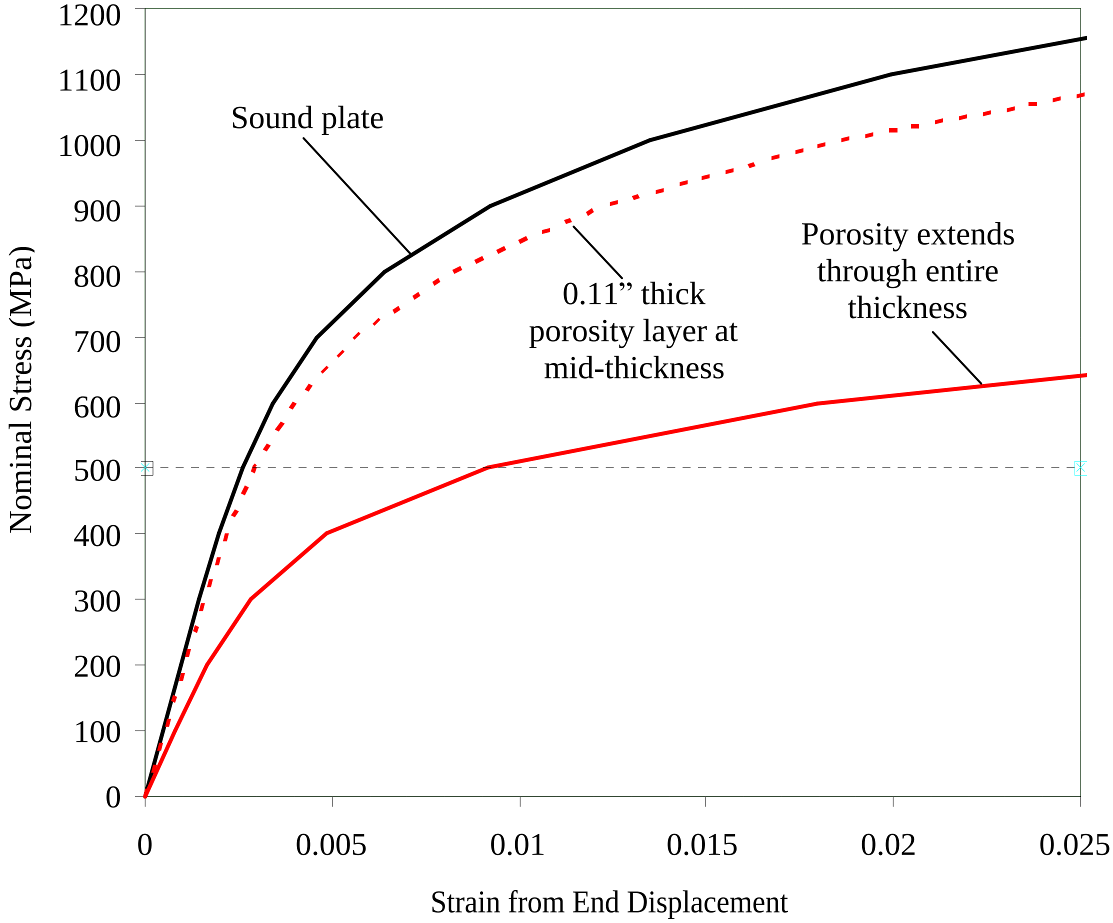

Fig. 5. Predicted stress-strain curves for the 1" thick plate of Figure 4. The three curves correspond to the porosity distributions shown in Figures 4(a), 4(c) and 4(e). The horizontal dashed line indicates the load of 500 MPa applied in the stress results shown in Figure 4.

For the plate shown in Figure 4(a), a designer could select the width of the plate as the feature length ($L_f = W$). Then, the maximum indication fraction is given by $F = l_{im}/W$ = 2.7"/5.5" = 0.49 = 49%. This value is the same as the reduction in the stiffness and load-carrying ability obtained for the porosity distribution of Figure 4(e). Hence, using $L_f = W$ is equivalent to assuming that the porosity extends through the entire thickness of the plate. For the porosity extending through the entire thickness, the lost cross-sectional area is given by $A_{im} = l_{im}T$; since $A = WT$, the maximum indication fraction becomes $F = (l_{im}T)/(WT) = l_{im}/W$. Clearly, this approach is conservative since radiographic indications typically do not correspond to voids that extend through the entire thickness of the casting section. Nonetheless, the example illustrates how the severity of the assumption that must be made about the depth of the voids can be controlled by the choice made for the feature length. In a less conservative approach, the designer could specify that $L_f = 9\,W$, which would imply that the voids extend through 1/9 = 11% of the thickness of the plate, as in the example of Figure 4(c). Then, F = 2.7"/(9 x 5.5") = 0.055, which results in a 5.5% reduction in the stiffness and load-carrying ability of the plate.

In another approach, the designer may select the thickness of the casting section as the pertinent feature length ($L_f = T$), such that the maximum indication fraction is given by $F = l_{im}/T$. This becomes necessary if, for example, the casting section being evaluated cannot be approximated as a plate-like shape and a relevant width, W, cannot be identified. The thickness T is, in all cases, the smallest dimension of the casting section. Thus, using $L_f = T$ to scale the maximum indication length l_{im} results in the largest possible indication fraction F (which is then limited by the acceptance level). Specifying $L_f = T$ is a very conservative approach. It is equivalent to assuming that the width available to carry the load is equal to the section thickness ($W = T$), as for a square bar, and that the voids corresponding to the radiographic indications extend through the entire thickness.

One could also assume that the thickness of the voids is equal to the measured indication length, l_{im}, such that $A_{im} = l_{im}^2$. This approach would approximately correspond to the voids having a square cross-section in the plane perpendicular to the direction of the loading. If one takes, in addition, $L_f = T$ (square bar with $A = T^2$), the lost cross-sectional area fraction is given by $A_{im}/A = l_{im}^2/T^2 = (l_{im}/T)^2 = F^2$. Hence, in this approach, the reduction in the stiffness and load-carrying ability is simply given by the square of the maximum indication fraction, F. A Level I casting section would then retain 99% of its stiffness and load-carrying ability, for example, while a Level V section would retain at least 75%.

Yet another approach would be to specify that the direction of interest is “any”, such that the largest total indication length, l_{im}, in any direction is measured. This approach would be appropriate if a relevant direction of interest cannot be identified. The designer could also request that the largest length, in any direction, of any single indication be used for l_{im}. The “directionless” approach can be used in conjunction with any choice for the relevant feature length, including $L_f = T$ and $L_f = W$, as discussed above. When used in conjunction with $L_f = T$, the “directionless” approach would likely result in the most stringent acceptance requirement.

The above discussion illustrates that the designer has numerous options in defining the maximum indication fraction, F, and then limit it by an acceptance level. If properly defined, the resulting estimate of the maximum lost cross-sectional area gives a direct indication of the reductions in the overall stiffness and load-carrying ability of the casting section. The loss of cross-sectional area is the main effect of the indications seen in radiography. The presence of the voids increases the stresses in the remaining cross-section, since the voids are not available to carry any of the load. Generally, the voids corresponding to radiographic indications should not be treated as pre-existing cracks, and the radiographic indication length should not be taken as a measure of an initial crack size. Instead, the maximum indication fraction, F, can be used to obtain an estimate of the magnitude of the stress enhancement resulting from the voids. The average stress in the remaining cross-sectional area is enhanced by a factor equal to $1/F$. This enhanced stress, which is greater than the nominal load, may then be employed by a designer to determine if the casting section still has sufficient strength or, in a fracture mechanics approach, to calculate a critical crack size that produces failure.

The maximum indication fraction, F, can also be used to estimate the effect of radiographic indications on fatigue crack initiation life for a casting section undergoing cyclic loading. The fatigue crack initiation life is calculated using the strain-life approach.[3] The voids corresponding to the radiographic indications are treated as notches. The enhanced stresses and strains at the notch root are obtained from the nominal stresses and strains using the fatigue notch factor. Figure 6 shows the relationship between the fatigue notch factor, K_f, and the maximum radiographic indication fraction, F. The data in this figure

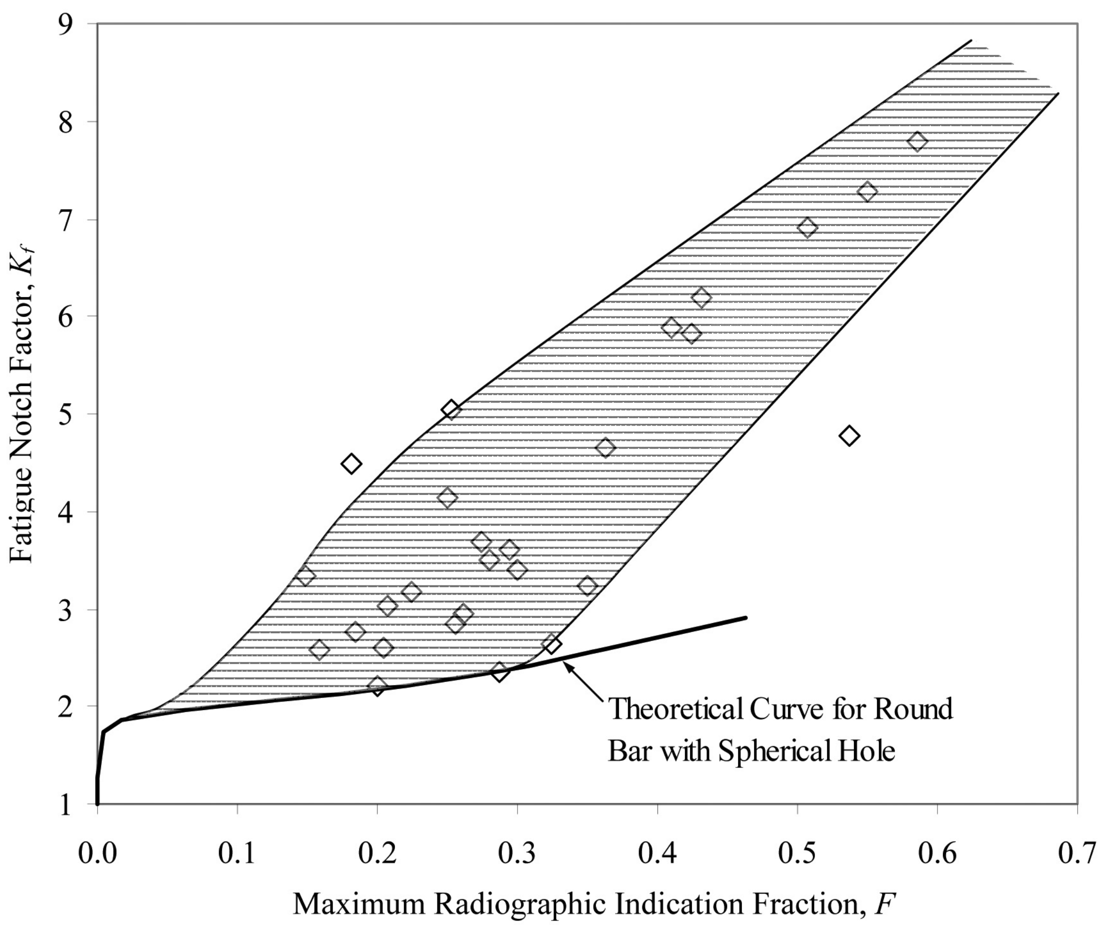

Fig. 6. Fatigue notch factor, K_f, as a function of the maximum indication fraction, F.

were obtained by matching measured and predicted fatigue lives for cast specimens with varying void fractions.[3] The fatigue notch factor increases with increasing size of the voids relative to the nominal cross-sectional area, as measured by the maximum indication fraction, F. For example, for a lost cross-sectional area percentage of 20% (F = 0.2) the fatigue notch factor is between two and four, while for F = 0.5 it is equal to about seven. The scatter in the data is due to the varying shape of the voids encountered in a casting. The lower bound is given by the fatigue notch factor for a spherical hole, for which the theoretical stress concentration factor is equal to about two. Once the fatigue crack initiation life is obtained, the remaining life of the component may be estimated using a fracture mechanics approach in which crack growth until failure is considered.

ADDITIONAL CONSIDERATIONS

The image of the casting section on the radiographic film is sometimes magnified or distorted, depending on the positioning of the source and the film as well as on the shape of the casting section itself. In that case, the indications visible on the film will not have the same size as the voids in the casting section. Image magnification and distortion are complex issues that require careful thought and considerable effort to resolve. The designer must consider these issues when specifying how the radiographic inspection is to be performed.

The precision of the indication measurements is limited by the radiographic sensitivity. In addition, factors such as geometric unsharpness also reduce the precision of the indication measurements. Furthermore, the indication measurements are performed manually, which can introduce errors. To account for these limitations, the maximum indication length measurements should only be considered accurate to within $1/16^{th}$ in (1.6 mm). This initial estimate of the measurement accuracy may be revised after further study. In any case, the designer must be aware of these limitations.

When specifying the feature length, L_f, the designer should be aware that the presence of machining stock and/or corrosion allowances may cause the casting to have larger dimensions than the part in service. The feature length should generally not include such stock or allowances.

RELATION OF PROPOSED STANDARD TO ASTM E186 REFERENCE RADIOGRAPHS

It is also of interest to explore the relation of the proposed standard to the ASTM E186 standard which provides reference radiographs for steel casting sections that are 2” to 4.5” thick. Figure 7 shows two examples of indication measurements performed on the reference radiographs. The area of interest was taken as the entire reference radiograph. The maximum total indication length, l_{im}, was measured for both horizontal and vertical directions of interest. In order to calculate the maximum indication fraction, $F = l_{im}/L_f$, the feature length was chosen to be the horizontal length (4.7”) of the reference radiograph for the horizontal direction of interest and the height (3.1”) for the vertical direction of interest. Only the shrinkage reference radiographs (CA, CB and CC) were analyzed.

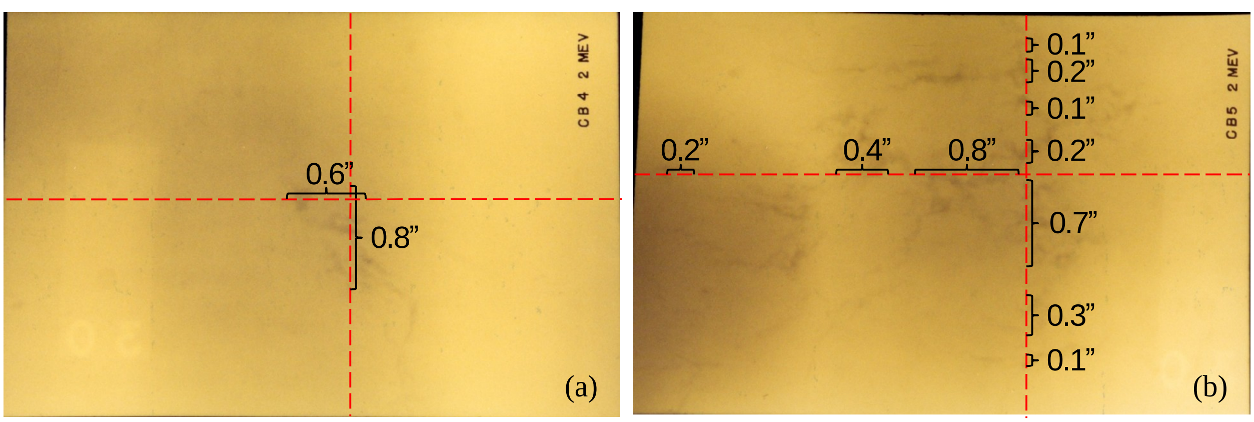

Fig. 7. Examples of measurements performed on the ASTM E186 reference radiographs to obtain estimates of the maximum indication fraction, F. (a) CB4: $F_{horizontal}$ = 0.6”/4.7” = 13%; $F_{vertical}$ = 0.8”/3.1” = 26%. (b) CB5: $F_{horizontal}$ = 1.4”/4.7” = 30%; $F_{vertical}$ = 1.7”/3.1” = 55%.

Figure 8 shows the results of these measurements. The data for each severity level was averaged over both directions of interest. It can be seen that, as expected, the measured maximum indication fraction, F, increases with increasing ASTM E186 severity level. However, large differences can be observed between the three types of shrinkage reference radiographs. The measured maximum indication fractions for Type CC are approximately twice as large as those for Types CA and CB. Also note that for Types CA and CB, the indication fractions for ASTM E186 Levels 2 to 4 are relatively close to each other (within about 10%), suggesting that it is difficult to discriminate between these levels when using the ASTM standard. Round robin studies have confirmed this poor discrimination.[1] In the proposed standard, no distinction is made between different types of indications and the acceptance levels in Table 1 are equally spaced at 10% intervals.

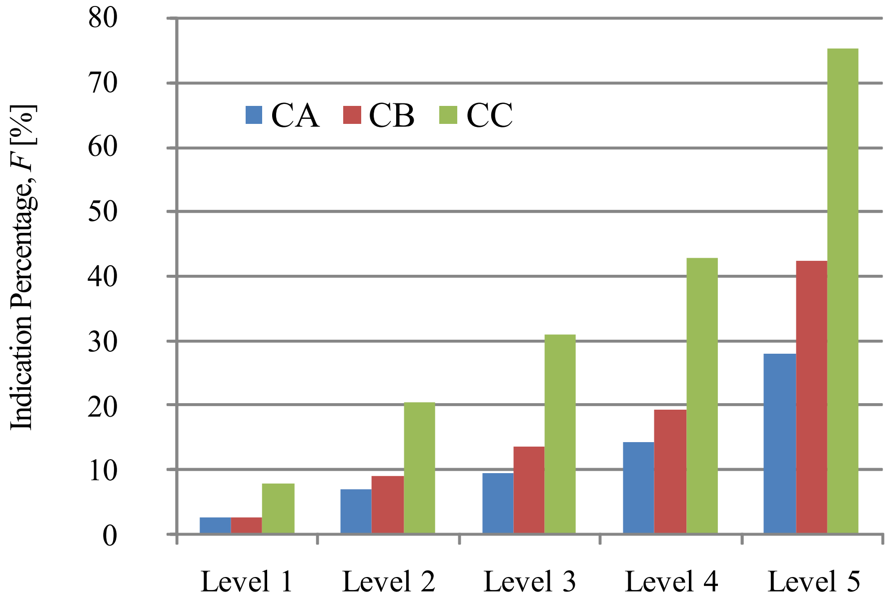

Fig. 8. Measured maximum indication fraction, F, as a function of severity level for the shrinkage reference radiographs of ASTM E186.

As discussed previously, in a conservative approach the indications on a radiograph can be assumed to correspond to voids in the casting that extend through the entire thickness of the section. Then, the maximum indication percentages shown in Figure 8 are equal to the percent reductions in the stiffness and load-carrying ability of the casting section. For example, an ASTM E186 Level 4 casting section with Type CA or CB indications would conservatively have its stiffness and load-carrying ability reduced by less than 20%.

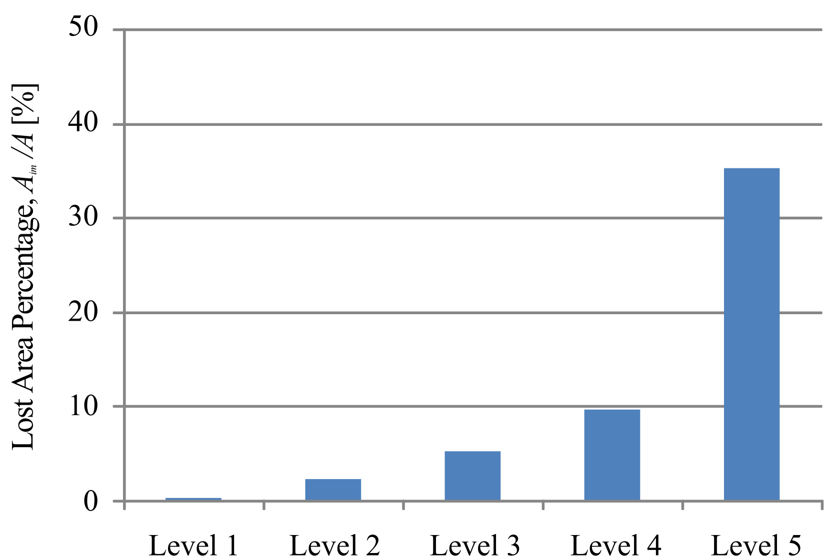

Figure 9. Lost cross-sectional area percentage as a function of severity level for the shrinkage reference radiographs of ASTM E186; the voids corresponding to the indications on the radiographs are assumed to have a square cross section inside of a 3” by 3” square bar.

In one of the other approaches discussed above, the voids corresponding to the radiographic indications are assumed to have a square cross section in the plane perpendicular to the loading direction ($A_{im} = l_{im}^2$), and the reference length is taken to be equal to the thickness of the section ($L_f = T$), which corresponds to a square bar of sound cross-sectional area $A = T^2$. The present indication length measurements on the ASTM E186 shrinkage reference radiographs can also be processed in this manner. Since the reference radiographs are for section thicknesses of 2” to 4.5”, a thickness of T = 3” is assumed. Figure 9 shows the resulting lost cross-sectional area percentage, $A_{im}/A = (l_{im}/T)^2$, as a function of the ASTM E186 severity level. The data was averaged over all three shrinkage types (CA, CB and CC) and both directions of interest (horizontal and vertical). The overall nature of the graph in Figure 9 is similar to the one in Figure 8, but the percentages are generally lower. For the present approach with T = 3”, ASTM E186 Levels 1 to 4 give reductions in the stiffness and load-carrying ability of less than 10%, while Level 5 gives a 35% reduction.

ACKNOWLEDGMENTS

This work is conducted under the American Metalcasting Consortium’s (AMC) Castings for Improved Readiness Program, which is sponsored by the Defense Supply Center Philadelphia, Philadelphia, PA and the Defense Logistics Agency, Ft. Belvoir, VA.

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