Predicting the Occurrence and Effects of Defects in Castings

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Casting designs are generally based on strength of materials calculations and the experience of the designer. This process leads to incremental development of designs utilizing factors of safety, which lead to increased component weights and inefficient use of materials. In castings, unquantifiable factors (such as shrinkage, porosity, hot tears, and inclusions) lead to conservative design rules. Nondestructive testing does not give the designer a way to assess the effect of indications on part performance. This article describes recent work to predict the occurrence and nature of defects in castings and determine their effect on performance.

INTRODUCTION

Designers are responsible for the performance of their designs. Traditionally, designers have used simple shapes and homogeneous material properties to determine the adequacy of their designs. A factor of safety is usually incorporated into a design to compensate for uncertainties caused by a complicated part shape, unknown service or load conditions, or undesirable manufacturing features. These factors of safety have resulted in reliable performance and, when adjusted or "tuned" based on performance testing, they have become the standard approach for most designs. Many designs are incremental, based on analogous parts in prior designs. In high-volume transportation applications, such as in the automotive industry, durability and warranty experience allow designs to be customized to give optimal performance. In critical applications where performance is at a premium, such as in the aerospace industry, safety margins are reduced through the use of extensive engineering modeling, durability testing, and nondestructive examination.

Designing castings is difficult. Casting complex shapes is limited by solidification behaviors that can result in undesirable features that may affect performance. While commonly called defects or discontinuities, these features are not necessarily the result of poor practice or lack of effort. These features can be controlled by special casting techniques or they can be removed and replaced by welding. Designers are uncomfortable with this aspect of casting design, and yet they must use castings to achieve performance in the most demanding applica-
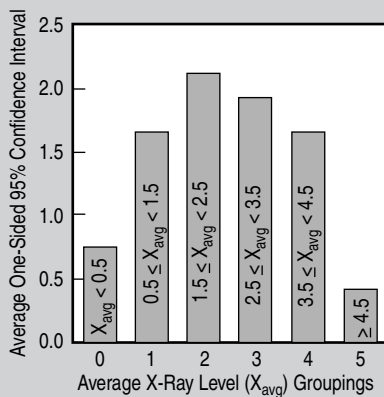

Figure 1. Average one-sided confidence intervals (CI) of ASTM x-ray level ratings, grouped by average x-ray level; average CI for all ratings is 1.42 levels.[4]
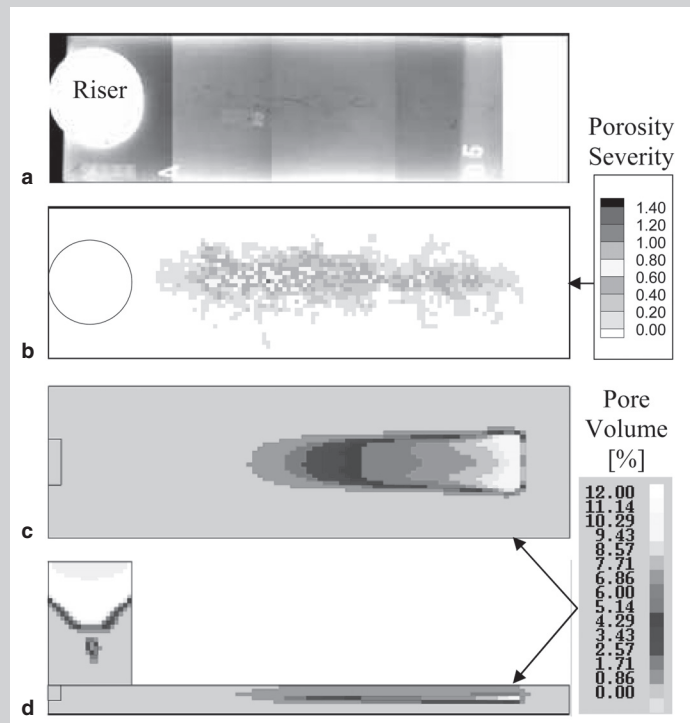

Figure 2. A comparison of experimental and simulated porosity distributions in plate castings made of low-alloy steel; porosity in castings is controlled by the riser system design.[2,3] (a) A top-view radiograph of one of the 15 plates, showing centerline shrinkage porosity; (b) a map showing average experimental porosity distribution for all 15 plates; (c) the top-view and (d) side-view cross-sectional simulated porosity results for the plate shown in (a).
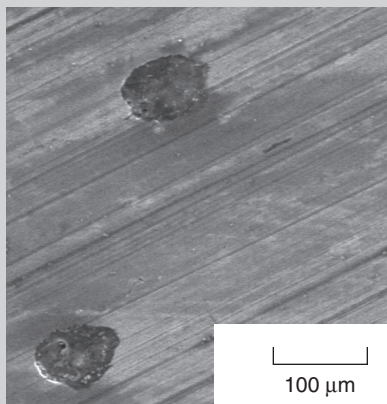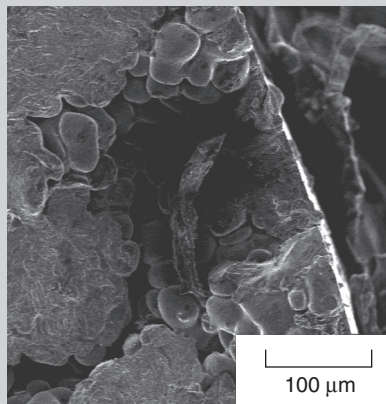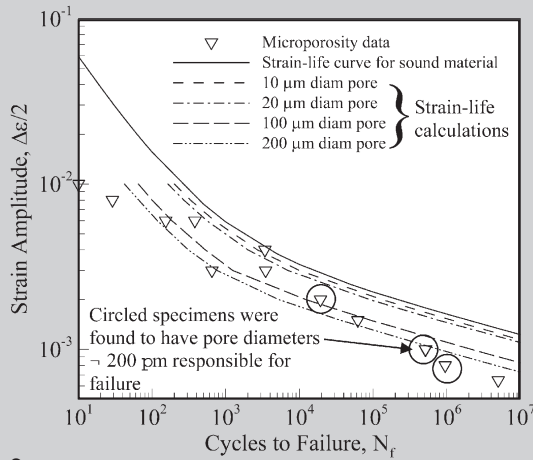
Figure 3. The effect of microporosity on fatigue properties of 8630 cast steel.[6] (a) Typical micropores of about 10 μm diameter found on the polished surface of specimens; (b) a scanning electron microscope image of near-surface micropores, approximately 200 μm in diameter, on the fracture surface; (c) strain-life curve for sound material, microporosity data, and model calculations for microporosity specimens using 10 μm, 20 μm, 100 μm, and 200 μm diameter surface notches.

tions or in the most complex geometries. Extensive nondestructive evaluation is often required by the purchaser to reduce the perceived risk of uncertain casting quality. Unfortunately, these nondestructive examinations are not engineering standards and have little relationship to part performance. These standards are often subjective and would fail common requirements for reliability.

Campbell[1] provides an overview of the deleterious effects of defects on casting properties in which he addresses this issue: "the size of the defect is often of much less importance than its form and position. For instance, a large pore in a low stressed area of the casting may be far less detrimental than a small region of layer porosity in a sharp corner subject to a high tensile stress. To have blanket specifications requiring elimination of all types of defect from every area of the casting is therefore not appropriate, and has resulted in the scrapping of many serviceable castings."

Casting producers are normally outside suppliers and not typically involved in the design process. As a result, the design may be difficult to cast and will be a source for much of the lack of quality and reliability. The designer unfamiliar with casting practices may create a geometry that is poorly suited to casting, is inefficient, and imposes nondestructive requirements and tolerances that are difficult to achieve and unnecessary for meeting the performance requirements. An inefficient design process is a major problem in the effective use of castings. Computer modeling approaches in design, manufacturing, and nondestructive evaluation are making possible real progress toward more reliable and efficient design of castings. This article reviews current activities in the development of integrated approaches to design that tie together service performance, manufacturing, and quality assurance. Even though most of the results presented are for steel castings, the general approaches are believed to be applicable to other cast materials.

SHRINKAGE AND POROSITY

Nondestructive evaluation (NDE) methods used for castings include sur-

face inspection and volumetric inspection. Surface inspection of a part can be visual examination or the use of magnetic particle or liquid penetrant techniques. Volumetric inspection includes radiography and ultrasonic examination. These techniques are intended to classify the magnitude of surface and internal indications. ASTM International and other standards organizations have a series of standards that seek to qualify these indications. However, the effect of the different quality levels on part performance has not been quantified. These standards are commonly referred to as "workmanship standards" and were not developed to predict performance.

Several attempts have been made to quantify shrinkage and porosity inspection results and relate them to casting performance.[2–9] A review of the interpretations of steel casting radiographs, by each manufacturer's NDE test facilities, raised a concern about the reliability of these interpretations. The result of a gage repeatability and reproducibility study utilizing 128 films and five film readers showed that while it was possible with some certainty to segregate the completely sound (level 0) and extremely unsound (level 5) indications, the discrimination of levels 1 through 4 was problematic, as seen in Figure 1.[4] The statistical evidence showed that the best that could be done was to measure shrinkage and porosity levels to an accuracy of ±1.4 levels (i.e., they are of little practical value). Attempts to characterize the different ASTM standard levels using computerized image analysis also met with little success. A lack of scaling, quantification, and location information poses a barrier to using the standard as it exists to predict part performance.

Ideally, the ability to predict the shrinkage and porosity seen in radiographs with casting simulation would be of great advantage. A multiphase (solid, liquid, and porosity) model that predicts melt pressure, feeding flow, and porosity formation and growth during solidification has recently been developed and implemented in a general-purpose casting simulation code.[5] The model is able to predict the location in a casting, amount (volume percentage), and size (diameter of individual pores) of both microporosity, which consists of tiny pores too small to be seen on radio-

graphs, as well as macroporosity, such as larger holes that form in castings when feeding flow is not available to a casting section during solidification. The results of an application of the model to predict macroporosity in a steel casting are given in Figure 2. This figure compares experimental porosity results (Figure 2a and 2b) with simulated porosity results (Figure 2c and 2d). Figure 2a shows a top-view radiograph of a 2.54 cm × 14.0 cm × 48.3 cm steel plate. A total of 15 such plates were cast in the experiments (five each from three different foundries), all using 7.62 cm diameter risers. The radiographs of each plate were overlaid with a fine grid, and the severity of porosity in each grid square was rated from 0 (no porosity) to 3 (severe porosity). After averaging the severity values over all 15 plates, a composite map of the average severity and location of porosity was obtained (Figure 2b). The wide band of macroporosity measured in this plate geometry is commonly referred to as centerline shrinkage. Figures 2c and 2d show top and side cross-sectional views of the predicted porosity distribution for the plate shown in Figure 2a. Good agreement between the simulation and experiment can be observed. Other validation studies have indicated that microporosity is also well predicted by the multi-phase model.[5,6]

Microporosity can be particularly troublesome, since it usually escapes radiographic detection and is known to be detrimental to ductility and fatigue properties. Fatigue test specimens were produced from AISI 8630 quenched and tempered steel castings.[6] Micropores of 10 μm to 20 μm diameter size and about 0.65 volume percentage were found dispersed uniformly throughout the specimens, as shown in Figure 3a on a polished cut section. Also, on three fracture surfaces, such as the one shown in Figure 3b, micropores as large as 200 μm in diameter were readily observed, since these pores were determined to be fatigue fracture initiation sites. The fatigue test results for these microporosity specimens are provided in the strain-life plot shown in Figure 3c. The solid curve in Figure 3c is the measured strain-life curve for the corresponding sound material without micropores.[7] Clearly, micropores can cause a reduction in the fatigue life of up to an order of mag-

nitude. Assuming that the micropores behave as spherical notches, strain-life calculations were made to determine the effect of pores having diameters of 10 μm, 20 μm, 100 μm, and 200 μm on the fatigue life (interrupted lines in Figure 3c). It can be seen that the strain-life calculation results for a 200 μm notch agree well with the measured fatigue lives of the three specimens found to have 200 μm diameter micropores on the fracture surface. This good agreement indicates that the reduction in fatigue life due to the presence of microporosity can be quantitatively predicted if the size of the micropores is accurately known. Since microporosity is generally undetectable by standard NDE, casting simulation that provides actual pore size information, as described, is of great value.

Macroporosity, on the other hand, is readily detected by radiography, but its effect on performance and fatigue life is not well understood. In a recent study,[6,8] mold geometries were designed to produce a range of macroporosity in AISI 8630 cast steel mechanical test specimens. A typical sectioned surface from a macroporosity specimen is shown in Figure 4a. Measurements were made of the apparent (or effective) elastic modulus of the macroporosity-containing specimens.[9] Figure 4b shows that the effective elastic modulus decreases linearly with increasing maximum sectional porosity measured from the specimen radiographs. Fatigue tests on the macroporosity specimens indicated substantial reductions in the fatigue life, relative to the microporosity results, as shown in Figure 4c.[6] The scatter in the data can be explained by the different macroporosity levels in the cast specimens. A fatigue notch factor, K_f, was back-calculated for each of the specimens using the measured apparent elastic modu-
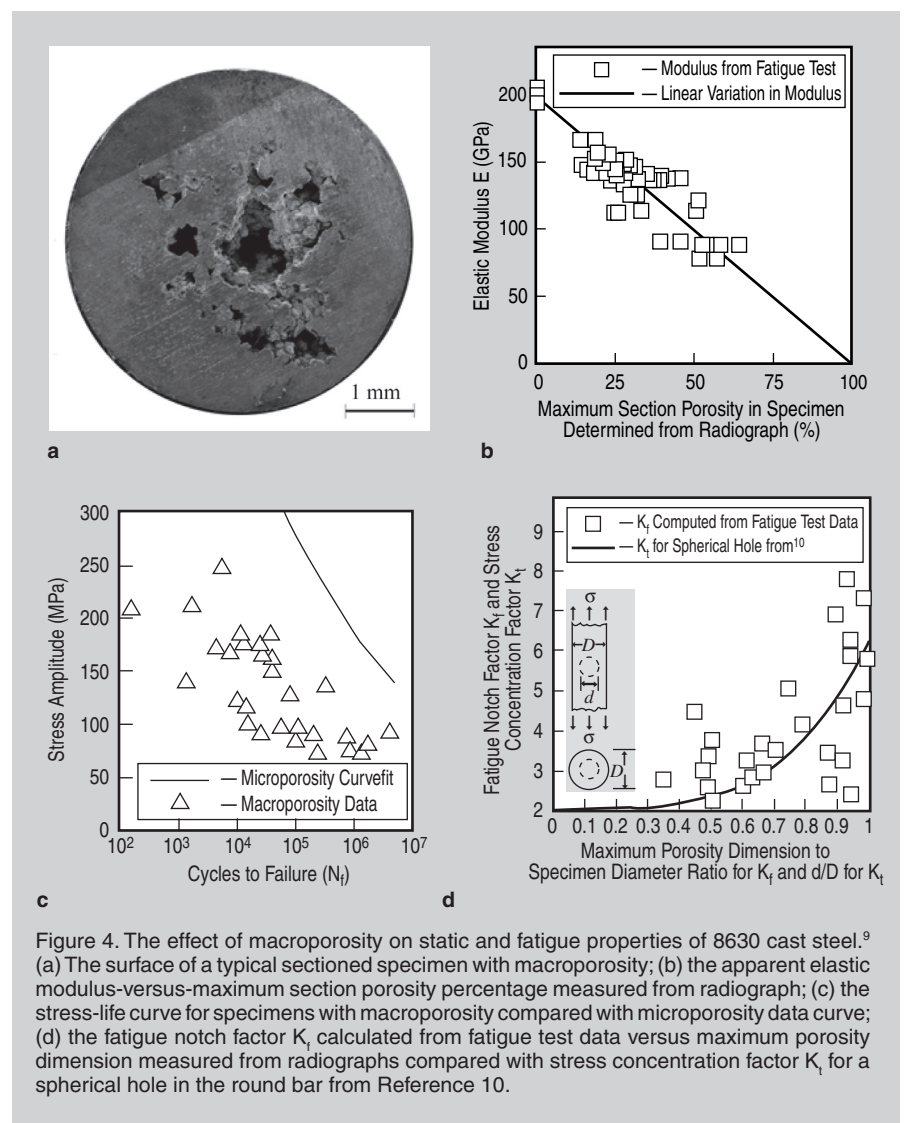

Figure 4. The effect of macroporosity on static and fatigue properties of 8630 cast steel.[9] (a) The surface of a typical sectioned specimen with macroporosity; (b) the apparent elastic modulus-versus-maximum section porosity percentage measured from radiograph; (c) the stress-life curve for specimens with macroporosity compared with microporosity data curve; (d) the fatigue notch factor K_f calculated from fatigue test data versus maximum porosity dimension measured from radiographs compared with stress concentration factor K_t for a spherical hole in the round bar from Reference 10.

lus, the measured fatigue life, and the local-strain life approach.[6] The fatigue notch factor determined in this manner is plotted in Figure 4d versus the ratio of the maximum pore dimension to the specimen diameter, which was measured from radiographs of each specimen. It can be seen that the fatigue notch factor increases with the size of the macropores. Also shown in Figure 4d (solid line) is the variation of the static stress concentration factor K_t (which should be larger than K_f) for a spherical hole of diameter d centered in a cylindrical section of diameter D subject to an axial stress.[10] Although the macropore shapes are much different from a spherical hole, the comparison in Figure 4d indicates that, as a first approximation, the fatigue notch factor for macropores may be calculated from available relations for spherical holes.[9]

These relations between porosity and mechanical properties, as well as the porosity distribution predicted by casting simulation, can then be used in finite-element stress and strain-life fatigue durability simulations to evaluate the service performance of a cast part. Example results for a case study involving a large steel casting are shown in Figure 5.[9] Figure 5a shows the predicted porosity distribution. The simulation reveals not only the large shrinkage indications that are rated in the ASTM standards, but also small microporosity (less than 1%) that is usually invisible on radiographic film. This porosity distribution is then transferred to the stress and durability codes. Figure 5b shows the predicted fatigue life distribution in the part without porosity, and with porosity taken into account in Figure 5c. For this particular case study the porosity does not appear to affect the fatigue life significantly. Nonetheless, the figure illustrates that porosity is acceptable in a casting at locations where it can be tolerated due to low stress levels, but soundness must be ensured in high-stress regions to achieve the desired fatigue life.

CRACKS AND TEARS

The classification of surface indications has been addressed by designers and standards developers in a similar manner to shrinkage and porosity. The existing ASTM standards are workmanship standards and have no clear relationship to the performance of parts in service. To date, they are the least-investigated aspect of casting design and production. Surface indications are not characterized in any published papers other than to address them as laps, cold shuts, cracks, linear indications, etc. Due to this lack of knowledge, surface indications are treated in an arbitrary manner where the designer will require that they must be reduced to a level that the foundry can live with and the purchaser can afford. The effect of the rectification process on the performance of the part has not been studied, but it is a commonly held belief that welding of these indications may produce a more deleterious effect than that of the untouched indication. A project is currently in the early stages to provide data as to the root cause of the indication, the depth of the indications into the casting, the sensitivity of the inspection techniques to small discontinuities (in terms of indication size), the differences in anomaly characteristics between magnetic particle indications and dye penetrant indications at the same level, and the ability of an operator to reliably discriminate between the different levels. In addition, efforts are underway to predict surface indications using casting simulation and quantitatively assess their effect on service performance.
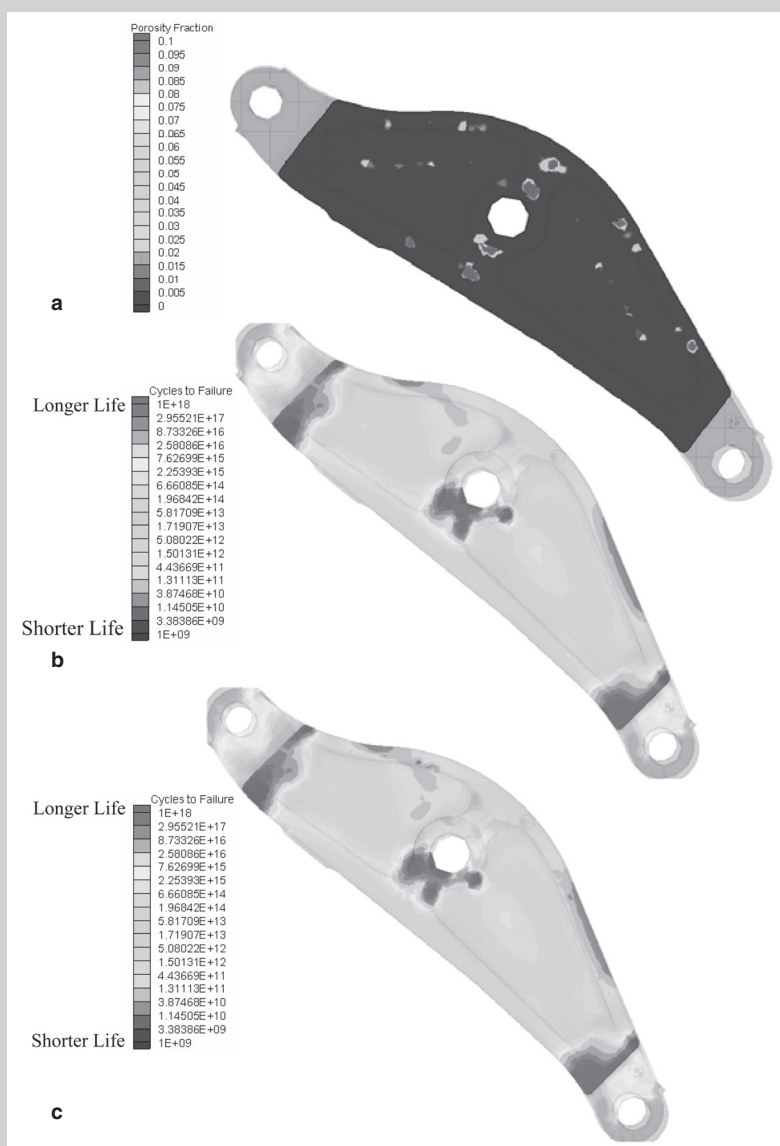

Figure 5. A case study illustrating the integration of porosity predictions into fatigue life simulations for a steel casting. (a) The predicted porosity fraction distribution in an interior section; (b) the predicted life distribution in loading cycles to failure without including effects of porosity; (c) the predicted life distribution in loading cycles to failure including effects of the porosity distribution shown in (a).

Hot tears are one example of surface indications in castings. Hot tears, which often result from the casting design,[11] occur when there is restraint in the casting during solidification, causing an unfed area in the casting to be pulled apart.[12] The ability to predict hot tear occurence is vital in developing casting designs that have significantly reduced hot tearing tendencies.[13] By combining feeding flow predictions (to detect the lack of feeding that would prevent a hot tear from healing) with stress modeling (to determine the strains during solidification), a hot tear indicator was recently developed for use in casting simulation.[14] Figure 6 shows an example of a hot tear prediction for a steel casting obtained in this manner, together with the corresponding casting trial results. This work is ongoing.[14]

INCLUSIONS

Inclusions represent another common indication in castings that is difficult to eliminate.[15,16] Inclusions are generally associated with the flow of liquid metal into the mold during pouring. However, modeling and verification trials in foundries have failed to indicate how gating systems may be universally improved.[17,18] Simple rules, such as filling the runner system as quickly as possible, have proven effective to some degree. Still, the fine tuning of gating systems to optimize their performance has been largely unsuccessful. While it is relatively easy to produce dirty castings with a bad gating system, the use of a good gating system does not necessarily lead to clean castings. It is well known that oxidation of the melt due to exposure to the atmosphere during mold filling is the root cause for the formation of a significant portion of the inclusions found in castings. For instance, in low-alloy steel, reoxidation inclusions account for 83% of all inclusions.[17] In steel castings, reoxidation inclusions are often found as discrete indications on the cope surface, as shown in Figure 7a and 7b. Campbell has extensively studied surface oxide films in aluminum castings.[19,20]

The problem with gating systems is directly linked to how the metal is delivered into the gating system, and each part of the delivery system cannot be treated in isolation.[19] Water modeling[17,21] has shown the highly variable nature of current pouring systems. Studies of the hydraulic issues and analysis[17] have shown that velocity is the largest single contributor to air entrainment in the gating system, and consequently the amount of inclusions is dependent on the air entrained. This is in agreement with the studies performed by Campbell.[20,21] A model has recently been developed to predict the formation and movement of reoxidation inclusions during filling of steel castings.[22] Figure 7c shows the results of a simulation that predicts the final location of inclusions in an experimental plate casting. It can be seen that a number of large inclusions, about 2 mm in diameter, are predicted at the cope surface of the plate, which qualitatively agrees with the corresponding casting trial results shown in Figure 7b. Research is currently underway to determine the effect of such inclusions on mechanical properties.

CONCLUSION

The need to design and produce lighter-weight and higher-performing castings will continue to increase in the future. The goal of the research programs described in this paper is to develop computer simulation methodologies to predict the performance of cast parts. The manufacturing process of a proposed design will be simulated, and the part performance will be assessed using realistic material properties that develop during manufacturing.

The acceptable design will have customized examination requirements allowing verification of part performance. The resulting designs should be less expensive to develop, requiring less time, testing, and design iteration. The manufacture of the parts should require less process development. The quality testing should be directly related to the
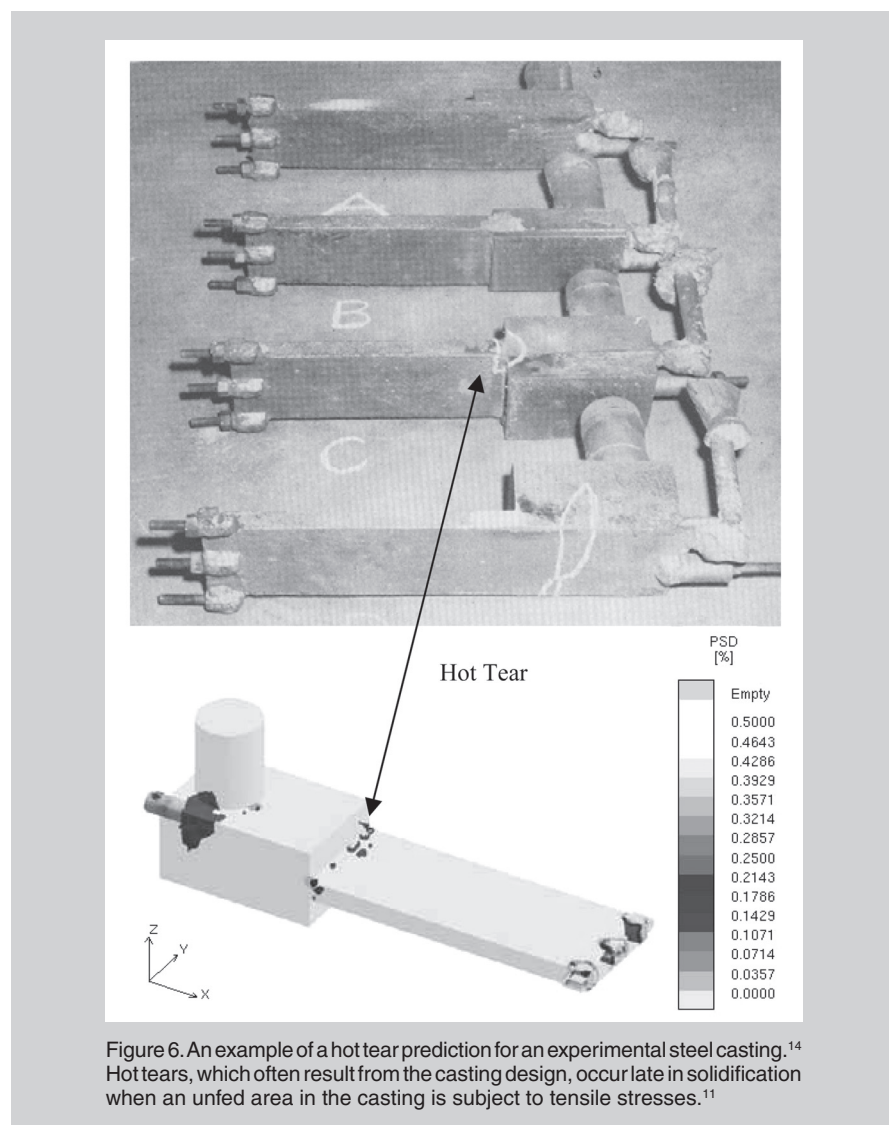

Hot Tear

Figure 6. An example of a hot tear prediction for an experimental steel casting.[14] Hot tears, which often result from the casting design, occur late in solidification when an unfed area in the casting is subject to tensile stresses.[11]

performance requirements. To meet these demands, simulation needs to be robust, and needs to predict to a high degree of reproducibility in the quality of the casting. Accomplishing this will require software that is able to predict the size and location of porosity, inclusions, hot tears, and other casting defects, as well as being able to interface with stress and durability analysis software. Finally, simulation will need to be able to produce custom standards capable of assuring part performance.

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Figure 7. A comparison of experimental and predicted reoxidation inclusion locations in a steel casting.[22] Inclusion formation in castings is primarily controlled by the pouring and gating system design.[1] (a) A typical reoxidation inclusion; (b) two experimental 2.54 cm × 25.4 cm × 30.5 cm plate castings (with inclusions circled); (c) top-view (upper image) and iso-view (lower image) of simulated inclusion distribution.

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