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PREDICTION OF MICROPOROSITY IN SHROUDED IMPELLER CASTINGS

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Abstract

The purpose of this Cooperative Research and Development Agreement (CRADA) between the Oak Ridge National Laboratory (ORNL) and Morris Bean and Company was to link computer models of heat and fluid flow with previously developed quality criteria for the prediction of microporosity in a Al-4.5% Cu alloy shrouded impeller casting. The results may be used to analyze the casting process design for the commercial production of 206 alloy shrouded impeller castings.

Test impeller castings were poured in the laboratory for the purpose of obtaining thermal data and porosity distributions. Also, a simulation of the test impeller casting was conducted and the results validated with porosity measurements on the test castings. A comparison of the predicted and measured microporosity distributions indicated an excellent correlation between experiments and prediction. The results of the experimental and modeling studies undertaken in this project indicate that the quality criteria developed for the prediction of microporosity in Al-4.5% Cu alloy castings can accurately predict regions of elevated microporosity even in complex castings such as the shrouded impeller casting. Accordingly, it should be possible to use quality criteria for porosity prediction in conjunction with computer models of heat and fluid flow to optimize the casting process for the production of shrouded impeller castings. Since high levels of microporosity may be expected to result in poor fatigue properties, casting designs that are optimized for low levels of microporosity should exhibit superior fatigue life.

CRADA Objective

Shrouded impellers are used in compressors for air-liquefaction. Aluminum-copper alloys have high yield strengths, thereby providing increased low-cycle fatigue strength. However, shrouded impeller castings made of aluminum-copper alloys are difficult to cast due to the propensity for microporosity formation in critical regions. The presence of microporosity greatly reduces the low cycle fatigue strength of the casting resulting in catastrophic failures during service. This project will link computer models of heat and fluid flow with previously developed quality criteria to predict microporosity in Al-4.5% Cu alloys, and predict microporosity distributions in a shrouded impeller casting. This will allow optimization of the casting process to result in a casting with acceptable levels of microporosity. The increased yield strength and improved low-cycle fatigue properties due to low microporosity levels in the optimized castings will enhance design performance, reduce energy costs, and enable castings to be used for new applications.

Assessment of CRADA

The results of the experimental and modeling studies undertaken in this project successfully showed that the quality criteria developed for the prediction of microporosity in Al-4.5% Cu alloy castings can accurately predict regions of elevated microporosity even in complex castings such as a shrouded impeller casting. Accordingly, it should be possible to use quality criteria for porosity prediction in conjunction with computer models of heat and fluid flow to optimize the casting process for the production of shrouded impeller castings.

This work was supported through a Cooperative Research and Development Agreement with Morris Bean and Company (Yellow Springs, Ohio), sponsored by the Laboratory Technology Research Program, Office of Energy Research, U.S. Department of Energy, under contract DE-AC05-96OR22464 with Lockheed Martin Energy Research Corp.

Since high levels of microporosity may be expected to result in poor fatigue properties, casting designs that are optimized for low levels of microporosity should exhibit superior fatigue life.

CRADA Benefit to DOE

This CRADA has enhanced the capabilities and skills at ORNL in the areas of casting process design, process modeling, simulation of heat and fluid flow, and the prediction of microporosity in castings. This will improve the prospects of future projects on the processing of advanced materials. The project has also allowed ORNL to obtain information on a casting process for producing premium quality castings that could be applied to the commercialization of alloys developed in Department of Energy (DOE) programs.

The CRADA also successfully demonstrated the application of DOE technologies in the areas of casting solidification and process modeling to the solution of problems encountered in production castings in a commercial foundry. It has also demonstrated that DOE programs can allow small businesses to access the technology available at DOE laboratories.

Technical Discussion

Aluminum alloy castings are produced in a wide range of compositions for a variety of applications. The resultant mechanical properties of these aluminum alloy castings depend on composition, casting process, and heat treatment. However, an additional important criterion that determines the resultant mechanical properties is the level of porosity in the cast part. Porosity can be broadly classified into two types: (1) macroporosity, also termed shrinkage pipe or centerline shrinkage; and (2) microporosity, also described as interdendritic porosity or porosity that cannot easily be discerned by the naked eye. Macroporosity forms due to a lack of liquid available to feed shrinkage and is usually detected by means of radiography or ultrasonic inspection. Macroporosity can be eliminated by adequate feeding or risering. Microporosity results due to a combination of shrinkage and gas evolution and is dispersed and usually microscopic. It is usually undetected either by normal radiography or ultrasonic inspection. Microporosity can markedly reduce mechanical properties, in particular ductility and fatigue properties, even when present in very small amounts. Microporosity can also affect properties such as "pressure tightness" and surface finish. It is useful, therefore, to be able to predict the level of microporosity in a shaped casting.

Porosity Distributions in Aluminum Alloy Castings

The mode of solidification of an alloy, from the considerations of the feeding of solidification shrinkage, primarily depends on the freezing range of the alloy and its thermal conductivity. The freezing range of the alloy determines the temperature range over which the alloy is in a "mushy" stage. An alloy with a fairly short freezing range and relatively low thermal conductivity, such as a low alloy steel, tends to have a large difference in fraction solid (i.e., high thermal gradient) between the center and surface of the casting. For simplicity, this mode of solidification is referred to as skin freezing. Fluid flow to feed shrinkage is primarily through a central channel, and a lack of liquid available to feed shrinkage gives rise to macroscopic porosity called centerline shrinkage, usually detected by means of radiography or ultrasonic inspection. In an alloy such as aluminum with high thermal conductivity, thermal gradients are likely to be low; points that are widely spaced in a casting are likely to be at the same or similar temperature and fraction solid.

Castings of alloys of high thermal conductivity and a large freezing range such as aluminum alloys are mushy over the entire solidification process (i.e., mushy freezers), and fluid flow to feed shrinkage takes place through long, tortuous, interdendritic channels. The combination of the relatively high resistance to the flow of liquid metal through tortuous flow channels and the precipitation of dissolved gas in the liquid metal, usually hydrogen, toward the end of solidification, results in the formation of dispersed microscopic porosity, or microporosity. Figure 1 illustrates schematically, the solidification mode of a skin freezing alloy and a mushy freezing alloy.

(a)

(b)

Fig. 1. Freezing modes in (a) skin-freezing alloys such as low carbon steel, and (b) mushy freezing alloys such as aluminum.

Prediction of Macroporosity in Castings

Chvorinov's rule relates the solidification time of the riser or casting to the square of its volume-to-area ratio. The criterion for adequate riser size is the requirement that the riser retain liquid longer than the section of the casting to be fed. An extension to Chvorinov's rule relates the solidification time of a given casting cross section to the square of its area-to-perimeter ratio. This ratio, combined with a weighting factor based on shape and mold material, termed a modulus, can be computed for sections of a complex casting. The minimum requirement of progressive freezing is now indicated by a continuously increasing modulus from sections furthest from risers to the risers themselves. The ease of application of models based on calculations of section modulus, particularly when implemented on personal computers, have allowed them to be used in a great number of cases, including those involving complex geometries. However, the greater the deviation of the casting-mold geometry from a flat interface, the less straightforward its application.

Numerical heat transfer models based on the finite difference method (FDM) and finite element method (FEM) present a general method for determining the solidification behavior of castings and checking for progressive freezing (or the absence of macroporosity). Computer models largely eliminate the inaccuracies inherent in Chvorinov's rule-based approaches when applied to complex geometries. The most common application of numerical heat transfer models to predicting shrinkage porosity is the use of plots of "end of freeze" temperature isotherms. Plots of "end of freeze" isotherms check for the presence of progressive solidification resulting in the presence of open feed channels throughout the solidification process. If isotherms cross, "pinch", or "bridge", shrinkage porosity is likely to result at the location.

Quality Criteria for Predicting Microporosity in Aluminum Alloy Castings

While thermal models are widely available and have been applied for over two decades to the prediction of macroporosity, they have been less frequently applied to the prediction of microporosity. A number of studies linking thermal parameters calculated from thermal models to porosity in steel [1-4] and aluminum alloy [5-7] castings may be found in the literature. However, while criteria for the prediction of porosity have been successfully applied for steel, applications to aluminum alloys have been less successful. A recent study on Al-4.5% Cu alloy suggests that the dominating mechanism controlling porosity distribution varies with the type of alloy cast and with solidification conditions [8,9]. In particular, the study suggests that casting processes may be divided into four groups. Applicable quality criteria over a wide range of casting conditions may be summarized by means of a "process map" for porosity, such as the one shown in Fig. 2.

Group 1 consists of castings characterized by strongly directional heat removal, such as DC and continuous casting, and castings with chills, or castings of alloys with comparatively small mushy zones, including short freezing range alloy castings such as many steel castings. Since the directionality of the thermal profile dominates the behavior of Group 1 processes, transport parameters dominate feeding and are good measures of porosity distribution. The quality criteria for Group 1 castings include the thermal gradient, G , the isotherm velocity, R , and the ratio of thermal gradient to isotherm velocity, G/R , or its counterpart G^2/ϵ , where ϵ is cooling rate. Figure 3 illustrates a relation between G/R and porosity obtained for Group 1 castings of grain-refined Al-4.5% Cu alloy.

Fig. 2. Process map for porosity prediction for a wide range of alloys including short freezing range alloys such as steel, and long freezing range alloys such as aluminum, as well as a wide range of casting processes.

Group 2 processes consist of castings characterized by a predominantly mushy mode of freezing, such as castings of long freezing range alloys, and alloys of high thermal conductivity, such as aluminum and copper-based alloys solidified in insulating molds. In Group 2 castings, liquid to feed solidification shrinkage must be transported through an increasingly dense dendrite matrix; the variation of fraction solid from the riser to the casting location is considerably smaller than for Group 1 castings. Due to the fact that resistance to fluid flow to feed shrinkage in Group 2 castings is the total resistance from the riser to the freezing location (see Fig. 1), local parameters are not very effective predictors for porosity in these castings. Figure 4 illustrates quality criteria that have

Fig. 3. A porosity predictor curve indicating quality criteria for Group 1 casting processes (castings solidified against chills or otherwise dominated by directional heat removal during freezing).

shown to correlate well with porosity levels for Group 2 castings of grain refined Al-4.5% Cu alloy. It indicates that dramatically increased porosity is obtained at a casting location when the fraction solid in the riser exceeds 0.8 (80% solid) at the time that location is at the final stage of solidification.

Group 3 processes consist of castings that are solidified comparatively rapidly, such as permanent mold castings. Group 3 castings are characterized by a very fine dendrite arm spacing and very high isotherm velocities. Consequently, the controlling mechanism for porosity distribution in Group 3 castings is both resistance to fluid flow to feed shrinkage and the effect of surface tension of the liquid alloy; porosity decreases with increasing cooling rate but is shifted to higher levels for castings with higher isotherm velocities. However, the overwhelming effect is that of "bubble pressure" due to surface tension, $2\gamma/r$, where γ is vapor-liquid surface energy. The effect of "bubble pressure" in Group 3 castings is both to increase solid solubility of hydrogen in the solid, and due to the effect of Boyle's law causing the gas to occupy a smaller volume. Both effects result in lower porosity levels. Possibly due to the interplay of both transport factors and microstructural features in Group 3 castings, cooling rate and isotherm velocity promise to be a useful quality criterion for porosity prediction. Figure 5 shows the variation of porosity with instantaneous cooling rate for Group 3 castings of grain-refined Al-4.5% Cu alloy.

Fig. 4. A porosity predictor curve indicating quality criteria for Group 2 casting processes (long freezing range alloy castings solidified in insulating molds) indicating a sharp increase in porosity when the fraction solid in the riser increases over 0.8 fraction solid.

Fig. 5. A porosity predictor curve indicating quality criteria for Group 3 castings, such as permanent mold castings.

Group 4 processes consist of directional solidification processes, characterized by very high thermal gradients and low isotherm velocities. Feeding of solidification shrinkage is not a consideration in Group 4 castings, since the short mushy zones promote complete feeding of solidification shrinkage. Porosity is only due to the effect of gas; consequently, the only factor that effects porosity is bubble pressure. Since directional solidification processes operate at steady state, G and R are constant. The increase of any one parameter relative to the other effectively results in a shorter freezing time, a smaller dendrite arm spacing, and increased bubble pressure. Correspondingly, porosity decreases with an increase either in G or R. Again, cooling rate should be a valid quality criterion, although the curves may be shifted downward to lower porosity levels due to the considerably lower isotherm velocities.

The application of quality criteria in the computer-aided design and analysis of a casting process must be accomplished by a step-by-step procedure. The first step in predicting porosity distributions in alloy castings is a check for progressive feeding or the "bridging" of isotherms. This may be accomplished by the use of a thermal model, or in the case of thin-section or complex castings, a combination of fluid flow and heat transfer models to predict thermal behavior. Once a design, free of macroporosity or centerline shrinkage, is obtained, a more stringent analysis for the prediction of distributed porosity may be attempted. The first step in the analysis for distributed porosity is the determination of porosity predictor curves similar to Figs. 3 through 5 for the particular alloy and processing conditions, such as degassing level and grain refining. Then, appropriate quality criteria are selected based on the thermal condition at a particular casting location, and the porosity predictor curves are used to predict the percent porosity at a particular location. Figure 6 outlines the steps used in a typical analysis.

Project Description and Results

The purpose of the CRADA project involving Morris Bean and Company and ORNL was to link computer models of heat and fluid flow with previously developed quality criteria for the prediction of microporosity in Al-4.5% Cu alloy, and predict microporosity distributions in a shrouded impeller casting. The results would be used to analyze the casting process design for the commercial production of 206 alloy castings.

Specific tasks were as follows:

- Task 1 — Morris Bean provided molds and blueprints for a test shrouded impeller casting.
- Task 2 — ORNL poured test castings in the laboratory for the purpose of obtaining thermal data and conducting porosity measurements. Also, ORNL conducted an initial simulation of the test shrouded impeller casting and validated results with porosity measurements on test castings.
- Task 3 — At a meeting held at Morris Bean, results of the simulation were reviewed and a production casting was selected for analysis.
- Task 4 — ORNL conducted a simulation of the production casting and provided the results to Morris Bean.

Experimental Studies of Test Impeller Casting

Several plaster investment molds and test cylinders were provided by Morris Bean for thermal measurements and determination of thermophysical properties. Two molds were poured with Al-4.5% Cu alloy. The molds were placed on a large cast iron block measuring $54 \times 54 \times 3.8$ cm ($21 \times 21 \times 1.5$ in.) that served as a chill, to simulate the

Fig. 6. Steps in the computer-aided analysis of a casting process for a design to specified porosity levels.

process used by Morris Bean. One mold was instrumented with a total of six thermocouples, two in the casting cavity and four in the chill. The other mold was sectioned for analysis of porosity by density measurement. The molds were poured by normal gravity pouring through the opening at the top of the mold rather than the low-pressure bottom filling (LPBF) approach used at Morris Bean, as LPBF facilities were not available at ORNL. A pouring temperature of 720°C (1325°F) and a mold preheat temperature of 175°C (350°F) were used; the cast iron chill was not heated. Type K thermocouples connected to a PC-based data acquisition system were used for the thermal measurements. Thermocouples were placed at distances of 2.5 cm (1 in.) and 9.5 cm (3.75 in.) from the chill surface in the center of the mold cavity and at distances of 0.6 and

1.3 cm (0.25 and 0.5 in.) from the chill surface at the center and edge of the chill [at a radius of 9.5 cm (3.75 in.)]. Density was measured using the Archimedes technique of measurements of weight in air and water. The specimens were coated with a light lubricating wax for the measurements in water to prevent water from infiltrating surface pores. The percent porosity was calculated from the measured density, assuming a theoretical density for Al-4.5% Cu alloy of 2.8 g/cc.

Figure 7 shows a picture of the complete casting as removed from the mold. Thermocouples are visible at the top of the casting. Figure 8 shows a plot of the cooling curves obtained from the thermocouples. Figure 9 shows the casting poured for porosity measurements. Some porosity is visible at the top surface of the shroud and cold shuts are apparent at the top of the vanes of the impeller. Figure 10 shows the casting in Figure 9 sectioned for density measurement. Density coupons were obtained from the center section of Fig. 10 as shown in Fig. 11. Table 1 lists the measured densities for the coupons shown in Fig. 11.

Fig. 7. Complete casting as removed from the mold. Thermocouples are visible at the top of the casting.

Fig. 8. Cooling curves obtained from instrumented casting.

Fig. 9. Casting poured for porosity measurement.

Fig. 10. Casting sectioned for porosity measurement. Measurements were conducted on the center section.

Fig. 11. Schematic of center section of impeller indicating the location of coupons for density measurement.

Table 1. Measured densities for coupons obtained from the center section of the impeller.

Sample No.	Porosity (%)
1	0.28
2	0.19
3	0.22
4	0.17
5	0.24
6	0.28
7	0.32
8	0.37
9	0.36
10	0.33
11	0.40
12	0.38
13	0.50
14	0.59
15	0.54
16	0.53
17	0.53
18	0.57
19	0.64
20	0.28
21	0.49
22	0.33
23	0.59
24	1.56
25	2.09
26	1.57
27	2.59
28	2.37
29	1.11
30	0.98
31	1.04
32	1.44
33	2.24

The porosity measurements indicate that porosity is low in the central portion or hub of the impeller casting, ranging from about 0.2 to 0.6%. As might be expected, porosity is lowest next to the chill, and gradually increases to a maximum of about 0.6% in the portion of the hub furthest from the chill (coupons 1 to 19). However, porosity is significantly higher in the shroud region (coupons 23 to 28), increasing to over 2% at the top of the shroud. Porosity is also high in the vanes (coupons 30 to 33), and ranges from approximately 1 to over 2%. The high levels of porosity in the shroud, and particularly the vanes of the impeller, may be expected to significantly lower the fatigue life of the impeller.

Modeling of Test Impeller Casting

The first step in the modeling of the test impeller casting was the creation of the finite element mesh. Since no electronic data was available, a mesh of the impeller casting and plaster investment mold was created directly from the pattern blueprint using Patran™ software. External dimensions of the mold were obtained from measurements of the molds supplied by Morris Bean. The finite element mesh consisted of 120,000 nodes. Hexahedral elements were used wherever possible; however, the edges of the casting and the center of the hub required wedge and tetrahedral elements. Figure 12 shows the bottom and sides of the finite element mesh of the casting, including the shroud, risers, and central sprue. Figure 13 shows the top and sides of the mesh of the plaster investment mold, and Fig. 14 shows the mesh of the shroud and impellers as viewed from above.

Fig. 12. Finite element mesh of the entire shrouded impeller casting, including risers and central sprue/riser. The bottom of the casting is to the right of the figure.

Thermophysical properties used for the Al-4.5% Cu alloy were the same as those used previously for development of quality criteria [10]; properties for the mold were estimated based on published data for plaster [11]. The density of the plaster investment mold was estimated from actual measurements of mass and physical dimensions on test cylinders supplied by Morris Bean. Tables 2 and 3 list the properties used in modeling.

Fig. 13. Finite element mesh of the plaster investment mold as viewed from above.

Fig. 14. Finite element mesh of the impellers and shroud as viewed from above.

Table 2. Thermophysical properties for Al-4.5% Cu alloy used in modeling.

Temperature (°C)	Thermal conductivity (W/m/K)	Density (Kg/m ³)	Specific heat (KJ/Kg/K)	Fraction latent heat ^a
25	188.3	2800	0.866	---
300	192.5			---
547	192.5	2700	1.092	1.00
548	---	---	---	0.94
578	---	---	---	0.90
601.5	---	---	---	0.85
613	---	---	---	0.80
620	---	---	---	0.75
625	---	---	---	0.70
632	---	---	---	0.60
636	---	---	---	0.50
639	---	---	---	0.40
642	---	---	---	0.30
644	---	---	---	0.20
645	---	---	---	0.10
647	82.6	2630	1.058	0.00
800	85.5	2630	1.058	---

^aLatent Heat of Solidification = 388 KJ/Kg

Table 3. Thermophysical properties for plaster investment used in modeling.

Thermal conductivity (W/m/K)	Density (Kg/m ³)	Specific heat (KJ/Kg/K)
0.167	1100	0.837

The first step in the modeling was to confirm that solidification was progressive (see Fig. 6). Figure 15 shows the calculated temperature isotherms for the test impeller casting 144 s from the start of solidification. Figure 15 indicates that solidification is progressive from the chill and that no macroporosity is expected. Solidification is also progressive in the region of the impellers and occurs from the center of the impellers toward the shroud and hub. Consequently, quality criteria can now be used to determine the extent and distribution of microporosity in the casting. Since the casting is solidified directionally from a chill, it may be expected to exhibit Group 1 behavior. Accordingly, the quality criterion for determining the microporosity distribution is the ratio of thermal gradient to isotherm velocity, G/R . Figure 16 shows a map of the calculated G/R ratios at the eutectic temperature of 548°C as plotted on the impeller casting surface, and Fig. 17 shows the calculated G/R ratios in the casting cross section. Figure 16 indicates high porosity regions in the center of the vanes, in sections at the top of the shroud, and along the bottom of the shroud. Figure 17 further confirms that the hub portion of the casting may be expected to exhibit low levels of microporosity while elevated porosity levels may be expected in the shroud.

Fig. 15. Calculated temperature contours for the test impeller casting 144 s after the start of solidification.

A comparison of the predicted microporosity distributions in Figs. 16 and 17 and the microporosity distributions indicated in Fig. 9 and Table 1 indicate an excellent correlation between experiments and prediction. Both experiments and predictions indicate elevated microporosity levels in the shroud region. The actual values of microporosity in the elevated porosity regions in the shroud (1 to 2%) are also consistent with the expected values of microporosity as predicted from Fig. 3 for the low values of G/R calculated in the shroud region. Also, the casting exhibited cold shuts in the center of the vanes, while elevated levels of porosity are predicted in the center of the vanes in Fig. 16.

The above results indicate that the proposed quality criteria can accurately predict regions of elevated microporosity even in complex castings such as the shrouded impeller casting. Accordingly, it should be possible to use quality criteria for porosity prediction in conjunction with computer models of heat and fluid flow to optimize the casting process for the production of shrouded impeller castings. Since high levels of microporosity may be expected to result in poor fatigue properties, casting designs that are optimized for low levels of microporosity should exhibit superior fatigue life.

Fig. 16. Calculated G/R ratios at the eutectic temperature of 548°C plotted on the surface of the test impeller casting.

Modeling of Production Impeller Casting

The results of the modeling of the test impeller casting were presented at a review meeting at Morris Bean. Based on the positive results obtained with the modeling of the test impeller casting, it was decided to model a production casting. First, a finite element mesh of the production impeller casting was constructed using Patran™ software. Then the casting was modeled in a manner similar to the test impeller casting and temperature and G/R contour maps were produced. Figure 18 shows a temperature contour map of the production casting 53 s after the start of solidification. The results indicate that solidification is progressive from the chill, suggesting that G/R contour maps may be used to predict the microporosity distribution. Figure 19 shows a G/R contour map of the production casting. The results are very similar to those obtained for the test casting, suggesting that the porosity distributions in the production casting are likely to be very similar to those in the test casting. However, the low G/R regions appear to be smaller in size in the production casting, indicating that the regions of elevated microporosity may also be smaller in the production casting.

Fig. 17. Calculated G/R ratios at the eutectic temperature of 548°C plotted in the cross section of the test impeller casting.

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Report of Inventions

No inventions were made or reported regarding this CRADA. However, the interaction between ORNL and Morris Bean raised possibilities for the use of other ORNL technologies, such as the use of Gelcasting for the production of molds for casting.

Commercialization Possibilities

The technologies demonstrated in this CRADA are well suited for application to the optimization of commercial castings. The only requirement for the commercialization of the technologies demonstrated in this CRADA is the availability of a computer workstation and casting modeling software.

Plans for Future Collaboration

Future plans for collaboration include the continuation of this work either informally or through funding from other programs such as the MPLUS program and the assessment of other ORNL technologies such as Gelcasting for use by Morris Bean.

Conclusions

The purpose of this project was to link computer models of heat and fluid flow with previously developed quality criteria for the prediction of microporosity in Al-4.5% copper alloy, and predicted microporosity distributions in a shrouded impeller casting. The results could be used to analyze the casting process design for the commercial production of 206 alloy castings. Test impeller castings were poured in the laboratory for the purpose of obtaining thermal data and porosity distributions. Also, a simulation of the test impeller casting was conducted and the results validated with porosity measurements on the test castings.

A comparison of the predicted and measured microporosity distributions indicated an excellent correlation between experiments and prediction. Both experiments and predictions indicated elevated microporosity levels in the shroud region. The actual values of microporosity in the elevated porosity regions in the shroud (1 to 2%) were also consistent with the expected values of microporosity as for the low values of G/R calculated in the shroud region. Also, the casting exhibited cold shuts in the center of the vanes, while elevated levels of porosity were predicted in the center of the vanes.

Results of the experimental and modeling studies undertaken in this project indicated that the quality criteria developed for the prediction of microporosity in Al-4.5% Cu alloy castings can accurately predict regions of elevated microporosity even in complex castings such as the shrouded impeller casting. Accordingly, it should be possible to use quality criteria for porosity prediction in conjunction with computer models of heat and fluid flow to optimize the casting process for the production of shrouded impeller castings. Since high levels of microporosity may be expected to result in poor fatigue properties, casting designs that are optimized for low levels of microporosity should exhibit superior fatigue life.