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Development of A New Criteria Function to Predict Microporosity in 319 Al-Si Castings

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ABSTRACT

The 319 Al-Si alloy is one of the most prominently used aluminium-based alloys in motor vehicle and engine applications. Microporosity present in 319 alloy castings reduces the load bearing capacity of the castings and may lead to leakage of fluids in certain applications. The quantitative prediction of microporosity levels in Al-Si castings has been a subject of much interest for several years. Among the various prediction methods, criteria functions have often been proposed as the solution, but so far an ideal criteria function has yet to be obtained for long freezing range alloys such as the 319.

Single solidification parameter and existing criteria functions have been evaluated for the quantitative prediction of the microporosity level in 319 Al-Si castings formed by the low pressure permanent mould process. In addition, an attempt has been made to develop a new criteria function based on multiple parameters. The thermal parameters associated with the solidification process have a strong impact on the formation of the microporosity in 319 Al-Si alloy. Two of the well-accepted existing criteria functions, Niyama and LCC, are not suitable for prediction of microporosity in 319 alloy under LPPM casting conditions. A new criteria function, $t_f^{1.98} R^{1.30}$ (t_f: local solidification time, R: cooling rate), has been developed by a series of multiple regression analyses, correlating thermal data from simulation studies to experimentally obtained microporosity values. This new criteria function can give a general prediction of microporosity in 319 Al-Si castings within a reasonable error.

INTRODUCTION

The 319 Al-Si alloy is a very popular alloy type with good castability and good mechanical properties. The high concentration of silicon improves the fluidity and hot tear resistance, while high copper content contributes to strength by precipitation hardening. These properties are particularly required to fabricate the complicated castings used in the motor vehicles and engines, such as oil pans, engine crankcases, etc. However, microporosity (micrometer scale cavities) usually found in 319 alloy castings, reduces the load bearing capacity and leads to leakage of fluids. Numerous studies have revealed that two major reasons are responsible for the microporosity formation in Al-Si alloys: hydrogen rejection due to a drastic reduction in the solubility from liquid to solid phase, and /or the volume contraction coupled with poor interdendritic feeding during the mushy zone solidification (Piwonka and Flemings, 1966; Talbot, 1989; Michels and Engler, 1989; Anson and Gruzleski, 2001). The quantitative prediction of microporosity levels in Al-Si castings has been a historically difficult problem due to the complexity of the issue. In the past years, a variety of methods have been proposed to determine the relationship between the casting conditions and the porosity level in castings. These methods can be classified into three main groups: criteria functions, integrated mathematical models combining hydrogen precipitation and interdendritic feeding, and micro-models.

The criteria function method is based on experimental observation or theoretical derivation. Since large amounts of experimental research have shown that solidification (thermal) conditions have a strong impact on porosity formation, it is believed that some thermal parameters (e.g. thermal gradient: G, cooling rate: R, solidification time: t_f, and solidification velocity: V_s) or their combinations may be used for determining the porosity level in castings. These thermal parameters or their combinations are termed criteria functions. By a series of theoretical and mathematical analysis of experimental data, the percent porosity can be calculated directly from the derived equation. The second group is called the integrated mathematic models method, considering the combining effects of the two main reasons for microporosity formation in Al-Si alloys: hydrogen evolution and poor interdendritic feeding. The models were built to find numerical solutions to Darcy's law coupled with energy, mass and momentum conservation as well as continuity equations (Kubo and Pehlke, 1985; Poirier et al., 1987; Fang and Granger, 1989; Suri and Paul, 1993; Huang and Conley, 1998). Nevertheless, the quantitative prediction microporosity becomes difficult because various assumptions must be made and further research is needed to improve the models. The third group is called the micro-models approach. The approach adds the alloy microstructure factor to the mathematic models (Yeum and Poirier, 1988; Fang and granger, 1989; Zuo et al., 1990). The mechanisms for pore nucleation and growth in the interdendritic or intergranular spaces were considered to estimate the pore size and volume percentage. In the models many assumptions are set under ideal conditions. Sufficient experimental data are needed to modify and verify the existing models.

By comparison, the criteria function method appears more attractive for its simplicity. The integrated mathematical models and the micro-models approach are too computationally intensive to be used for industrial practice. With the development of computer simulation and statistical analysis software, it is now possible to quantitatively study the relationship between the solidification parameters and porosity level in castings before their production. Since Niyama pioneered the criteria function $G/R^{1/2}$ to successfully predict the centerline shrinkage in steel castings in 1982 (Niyama et al., 1982), many other criteria functions have been proposed for microporosity prediction in Al-based alloys: $Gt_f^{2/3}/V_s$ (Lee et al., 1990), $1/(G^{0.475}V_s^{0.317})$ (Suri et al., 1994), $G^{0.38}/Vs^{1.62}$ (Chang and Kuo, 1996), and $G/(R^{1/2}t_f^{3n})$ (Chen and Ravindran, 1999) for A356 alloy as well as $G/(V_s t_f^{1.1})$ (Chang and Kuo, 1994) for A201 alloy. However, there is a noticeable lack of research on the microporosity prediction in the typical used 319 alloy under the low pressure permanent mold (LPPM) casting conditions, which are used predominantly for the production of aluminum-base alloy castings in the automotive industries (Clegg, 1991).

In this study, single solidification parameters (t_f, G, R, V_s) and two well-accepted existing criteria functions (Niyama: $G/R^{1/2}$ and LCC: $Gt_f^{2/3}/V_s$) have been evaluated for the quantitative prediction of the microporosity level in 319 Al-Si castings formed by the LPPM process. In addition, an attempt has been made to develop new criteria functions based on multiple regression analysis by correlating the simulated thermal data to the measured microporosity (%) from experimental samples.

EXPERIMENTAL PROCEDURE

The experimental work consists of four main parts. The first step was to select the commercial 319 alloy used in the automobile industry. The second step involved the sample design considering the structure factor of castings with different cross-sections and convenience for simulating thermal parameters. The third step related to sample preparation with the low pressure permanent mould casting process and the simulation of thermal data by computer modelling. Finally, local percent microporosity in plate castings was determined corresponding to specific locations. The measured microporosity level in plate castings and simulated thermal data provide the data source to do the statistical analysis to evaluate the effectiveness of existing criteria functions and to develop new criteria functions. Figure 1 shows the flowchart of the entire experimental procedure.

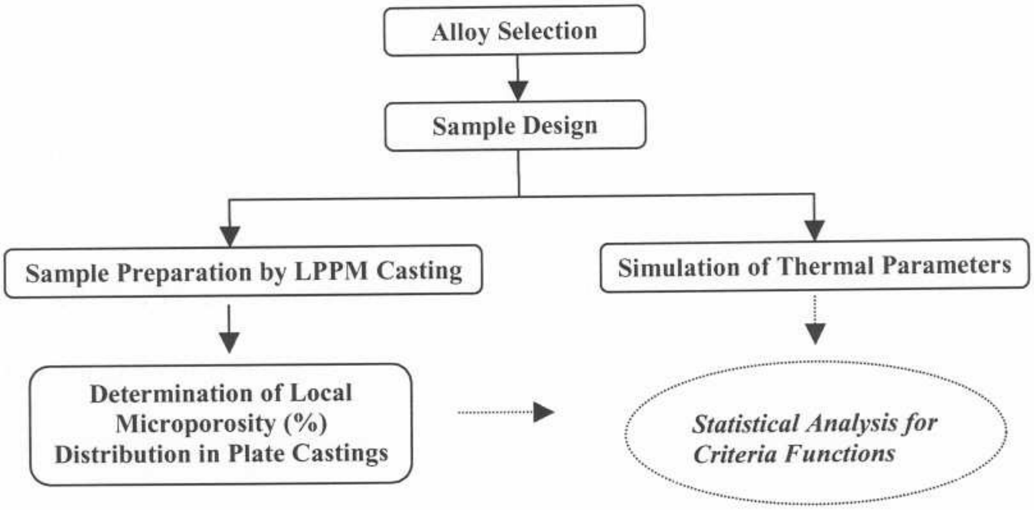


Fig. 1. Experimental procedure flowchart

EXPERIMENTAL MATERIALS

A commercial 319 alloy was employed in the present work. Its chemical composition is given in Table 1. The alloy was modified with 180 ppm strontium.

Table 1 Chemical compositions of the 319 alloy (in wt. %)

Alloy	Si	Fe	Cu	Mn	Mg	Zn	Ti	Al
319 Al-Si-Cu	6.25	0.42	3.62	0.28	0.06	0.53	0.16	Balance

SAMPLE DESIGN

Four plate samples with different thicknesses were designed in one die to create various solidification conditions. The structure of the die was described in a previous study on thermal analysis (Paray et al., 1996 and 1997). The plate geometry was selected based on the consideration that the simple plate shape is a basic form found in castings, and is easy for thermal modeling. The plate castings are shown in Figure2. The four plate thicknesses are 3.2 mm, 6.4 mm, 12.7 mm and 19.1 mm. The length and width of the plates are 279.4 mm and 101.6 mm, respectively, and the sizes of the gates are 50.8 mm in width with a thickness ratio of 2/3 between the gates and the plates.

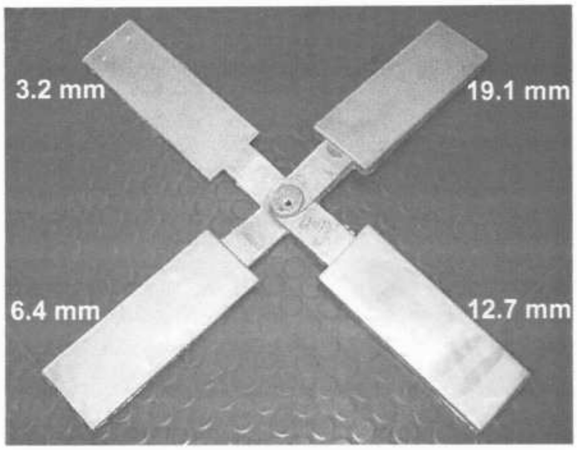


Fig.2 Plate samples with four different thicknesses

CASTING PLATE SAMPLES

Plates samples were cast in an industrial environment using a low pressure permanent mould casting machine. A 2.1×10^4 Pa (3 psi) gauge pressure was used. The casting cycle time consists of 90 seconds cast time, 90 seconds cooling time and 31 seconds open time, for a total of 3.5 minutes. The hydrogen level of the melt was determined by a modified Straube-Pfeiffer test developed at McGill to give a quantitative value of the hydrogen content (La-Orchan et al., 1993; La-Orchan, 1994). The gas level measured in the melt was $0.20 \sim 0.30$ ml H_2/100g Al.

MICROMPROSITY (%) DETERMINATION

The microporosity volume percentage was determined by density measurement using Archimedes's principle. Each plate was sectioned into three parts along the length, referred to as the left, middle, and right slices. Each slice was then cut into nineteen small rectangular blocks (A-S from feeding end to free end) as shown in Figure 3. The density and percent microporosity of the small blocks were calculated by equation 1 and equation 2.

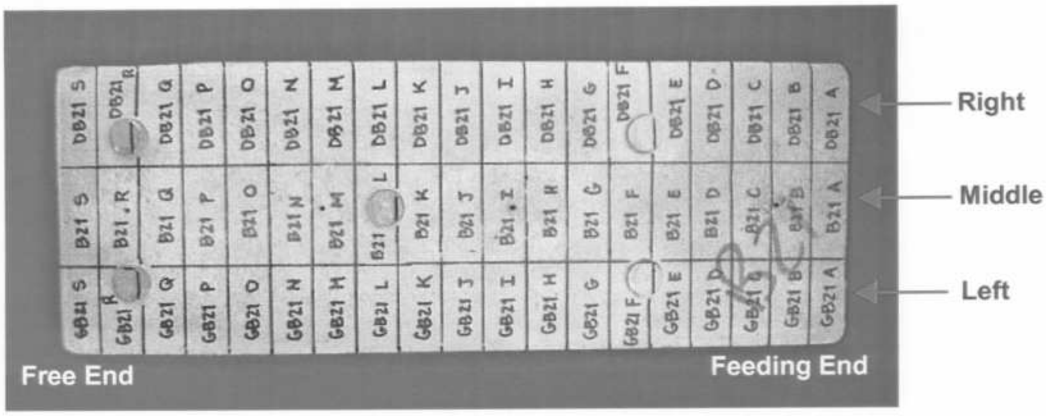


Fig. 3 The small blocks for microporosity determination

$$D_M = \frac{M_a}{(M_a - M_w)} \times D_w \qquad \text{Eq. 1}$$

$$\%P = \frac{D_T - D_M}{D_T} \times 100 \qquad \text{Eq. 2}$$

Where

M_a is the sample mass in air (g),

M_w is the sample mass in water (g),

D_M is the measured density of the small block sample ($kg{\cdot}m^{-3}$),

D_T is the theoretical density of 319 alloy, 2.788×10^3 ($kg{\cdot}m^{-3}$) calculated from sound disk samples cast in a copper mold,

D_w is the density of water (g/cm^3),

P is the volume percentage of microporosity (%)

SIMULATION FOR THERMAL PARAMETERS

Using the CASTVIEW simulation package, four kinds of thermal parameters were calculated corresponding to any location where the microporosity (%) was determined experimentally:

t_f: local solidification time, s;

R: cooling rate at solidus, °C /s;

G: thermal gradient at solidus, °C/mm;

V_s: solidification velocity, mm/s.

The model data were validated by temperature measurements taken on the castings during solidification. Four locations along the central axis of the plate casting were selected to assemble thermocouples at the mid-points of the width and height in each plate cavity (Figure 4). Cooling curves were produced by recording temperatures versus time during solidification. Thus the transformation temperatures of the alloys, namely the solidus, liquidus and eutectic temperatures, were estimated. These values were used to determine the alloy properties to ensure that the simulated data are as close as possible to the actual values.

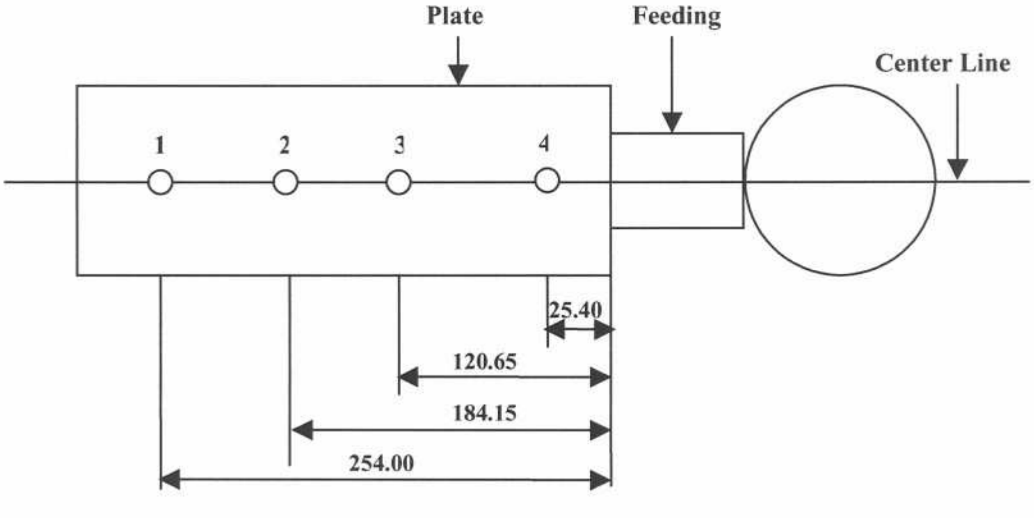


Fig. 4 Schematic diagram of the locations at which thermocouples were placed for temperature measurement

STATISTICAL ANALYSIS

Statistical methodology provides an effective way to study the relationship between thermal parameters and microporosity (%). Since thermal data is used for explaining microporosity levels, various thermal parameters or their combinations (criteria functions) are defined as the independent variables (denoted by X), while percent microporosity is defined as the dependent variable (denoted by Y) which is being predicted or explained. Table 2 displays the meanings of these variables.

Table 2 Nomenclature of dependent and independent variables

Dependent variable (Y) (measured)	**Independent variables (X) (simulated)**	
Microporosity P (%)	single parameter	local solidification time(s): t_f
		cooling rate (°C /s): R
		thermal gradient (°C/mm): G
		solidification velocity (mm/s): V_s
	existing criteria functions	Niyama: $G\cdot R^{-1/2}$
		LCC: $G\cdot t_f^{2/3}\cdot V_s^{-1}$
	new criteria functions	$f(t_f, R, G, V_s)$ new combinations of thermal and solidification parameters

REGRESSION ANALYSIS

Regression analysis (Anderson et al., 2001) is one of the most frequently used statistical techniques to analyze the relationship between two or more variables. This technique will establish a mathematical relation using the **Least Squares method**, minimizing the sum of the squared deviations (equation 3). This estimated regression equation (equation 4) indicates how Y varies with X.

$$\min \sum e_i^2 = \sum (y_i - \hat{y}_i)^2 \qquad \text{Eq. 3}$$

where,

e_i: the sample residual (error), the distance from the point (x_i, y_i) to the regression line

y_i: observed value of the dependent variable for the ith observation

$\hat{y}_i$: estimated value of the dependent variable for the ith observation

$$\hat{y} = b_0 + b_1x_1 + b_2x_2 + \cdots + b_px_p \qquad \text{Eq.4}$$

Where coefficients of b_0, b_1,b_2,….b_p are provided by the least squares method using sample data, and x_1,x_2,…, x_p are independent variables.

Five regression models shown in Table 3 (linear, logarithmic, polynomial, power, and exponential models) were used to find the best-fit regression equation. The effectiveness of four kinds of single thermal parameter (t_f, G, R, V_s) and two existing criteria functions (Niyama: $G \cdot R^{-1/2}$ and LCC: $G \cdot tf^{2/3} \cdot V_s^{-1}$) for predicting the microporosity (%) in the alloys was evaluated using these models. The analysis step begins with the data from each of the three different thicknesses to investigate the effect of the geometry factor (plate thickness) on the microporosity level. Since real castings always consist of different cross sections, the data combining the three thicknesses are then used to evaluate the effectiveness of microporosity prediction in practical casting situations.

Table 3 Regression models to evaluate single thermal parameter and existing criteria functions

Simple Regression Models	
linear	$Y = aX + b$
logarithmic	$Y = a \ln X + b$
polynomial	$Y = a X^2 + bX + c$
power	$Y = aX^b$
exponential	$Y = ae^{bX}$
Dependent variable (Y): microporosity (%) (measured from plate castings) Independent variables (X): thermal data defined in Table 2 (simulated)	

The method of multiple regression analysis was used to develop new criteria functions to predict microporosity. The commercial statistic software SAS 8.2 can be used, but only the general liner model (equation 5) is available. The mathematical relationship to be developed, however, is not a simple linear one. Based on the consideration of mathematical transformation, the regression model used was in the power form (equation 6) since it can be easily transformed into linear relations (equation 7). In equation 6 and equation 7, the dependent variable (P: percent microporosity) and independent variables (a series of thermal parameters: t_f, G, R, V_s) are as defined in Table 2, and the thickness of the plate casting (L) is added as another independent variable. Data input were the combined data from all three thicknesses of plates.

$$\hat{Y} = A + b X_1 + c X_2 + d X_3 + e X_4 + f X_5 \qquad \text{Eq. 5}$$

$$P = a \cdot t_f^{\,b} \cdot R^c \cdot G^d \cdot V_s^{\,e} \cdot L^f \qquad \text{Eq. 6}$$

$$\log P = A + b \log t_f + c \log R + d \log G + e \log V_s + f \log L \qquad \text{Eq. 7}$$

Independent variables are assumed to be not interactive. In practice, however, it is difficult to separate the effects of the individual independent variables on the dependent variable since some unavoidable interactions are present among the independent variables, e.g. temperature gradient and solidification velocity. To test the degree of correlation, the function of collinearity diagnostics was used in the software SAS 8.2. Generally, in multiple regression problems, a low degree correlation between independent variables does not affect the integrated regression analysis.

MEASURES OF THE GOODNESS OF FIT FOR A REGRESSION

The coefficient of determination (Anderson et al., 2001), denoted by r^2 (equation 8), indicates the percentage of variation of the dependent variable which can be explained by the independent variables. The coefficient of determination can have values between zero and one

$$r^2 = \frac{\sum(\hat{y}_i - \bar{y})^2}{\sum(y_i - \bar{y})^2} \qquad \text{Eq.8}$$

In this research, y_i is the measured value of microporosity (%), $\hat{y}_i$ is the estimated value of microporosity (%), and $\bar{y}$ is the mean value for the measured microporosity (%). The r^2 value shows the percentage of microporosity level in castings that can be explained by the thermal data. The greater the r^2 value, the better the goodness of fit of predictive equation.

RESULTS AND DISCUSSION

LOCAL MICROPOROSITY DISTRIBUTION IN PLATE SAMPLES (%)

The microporosity distributions in plate castings with different thicknesses (6.4 mm, 12.7 mm and 19.1 mm) are compared in Figure 5. Each point on the graph corresponds to the specific location of small block samples, and every point represents the average calculated from four randomly selected samples. Only the side slices were used for the data source since some massive macroshrinkage was found in the middle slices of the plate castings. In addition, a few values greater than 2%, which relate to open macroshrinkage pores, were also removed from the data set. The results indicate that the thicker the cross-section of the sample, the higher the microporosity level. This is due to fact that the lower cooling rate and longer solidification time in the thicker plates lead to a greater amount of microporosity. It is also noted that the microporosity is much greater in the middle than at the two ends because of the late solidification in the middle zone. Moreover, the microporosity distributions for the left and right side slices are not identical due to the slightly different solidification conditions caused by the adjacent plate, which may be thicker or thinner depending on location. As a result, the heat flux during solidification is different for the left and right sides of each plate.

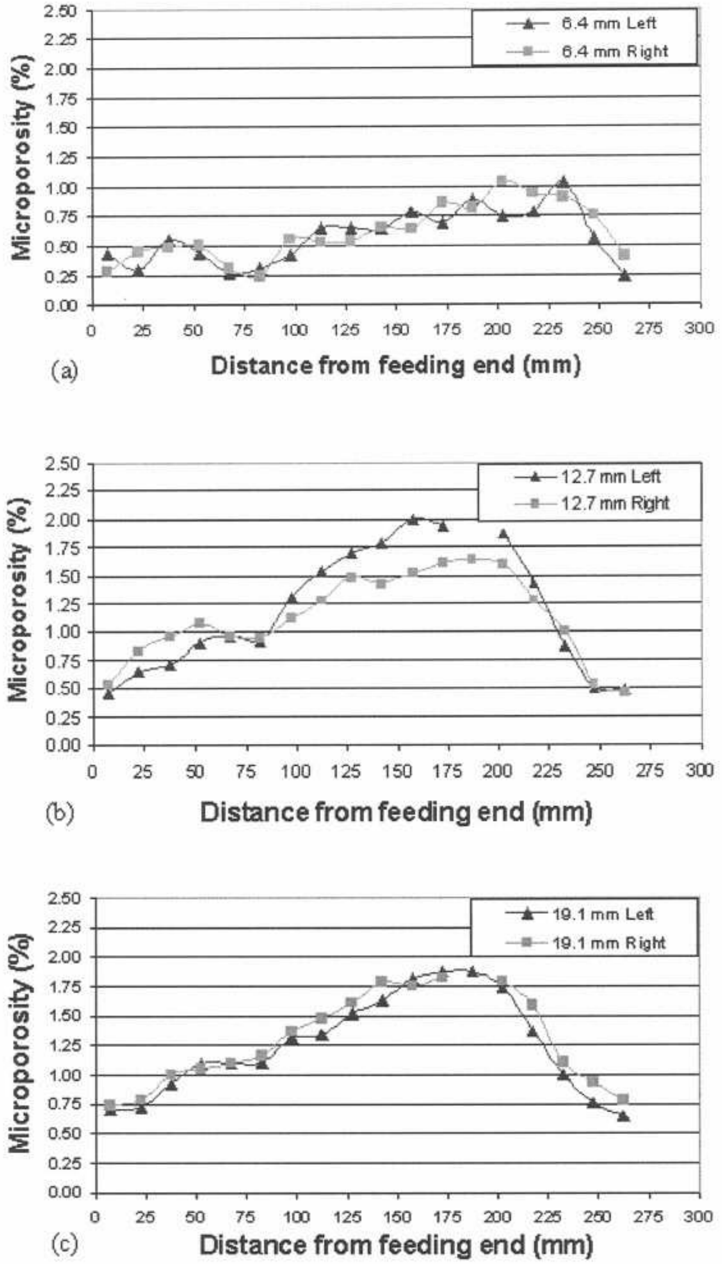


Fig. 5 Typical microporosity distribution in different thickness plates for the 319 alloy
(a) 6.4 mm thickness, (b) 12.7 mm thickness and (c) 19.1 mm thickness

THERMAL PARAMETERS

Thermal data from simulation

Four kinds of basic thermal data: local solidification time (t_f), thermal gradient (G), cooling rate (R), and solidification velocity (V_s), were simulated corresponding to different locations in the plate castings. As an illustration, Figure 7 displays the distribution of local solidification time versus specific location (distance from feeding end) in plate castings with different thicknesses. Signs of a decreasing local solidification time are first observed at the two ends of the thicker plates (12.7 mm and 19.1 mm) due to a higher cooling rate. The thinner plates (6.4 mm) have a more uniform distribution of local freezing times due to relatively equal cooling rates within the plates. The slight difference in thermal conditions for the left and right slides also can be noted due to the effect of the adjacent plates. There is a distinct 3 ~ 9 seconds difference between the left and right sides of the 12.7 mm and 19.1 mm thickness plates. The values are almost same for the thinner (6.4 mm) plates due to their higher overall cooling rates.

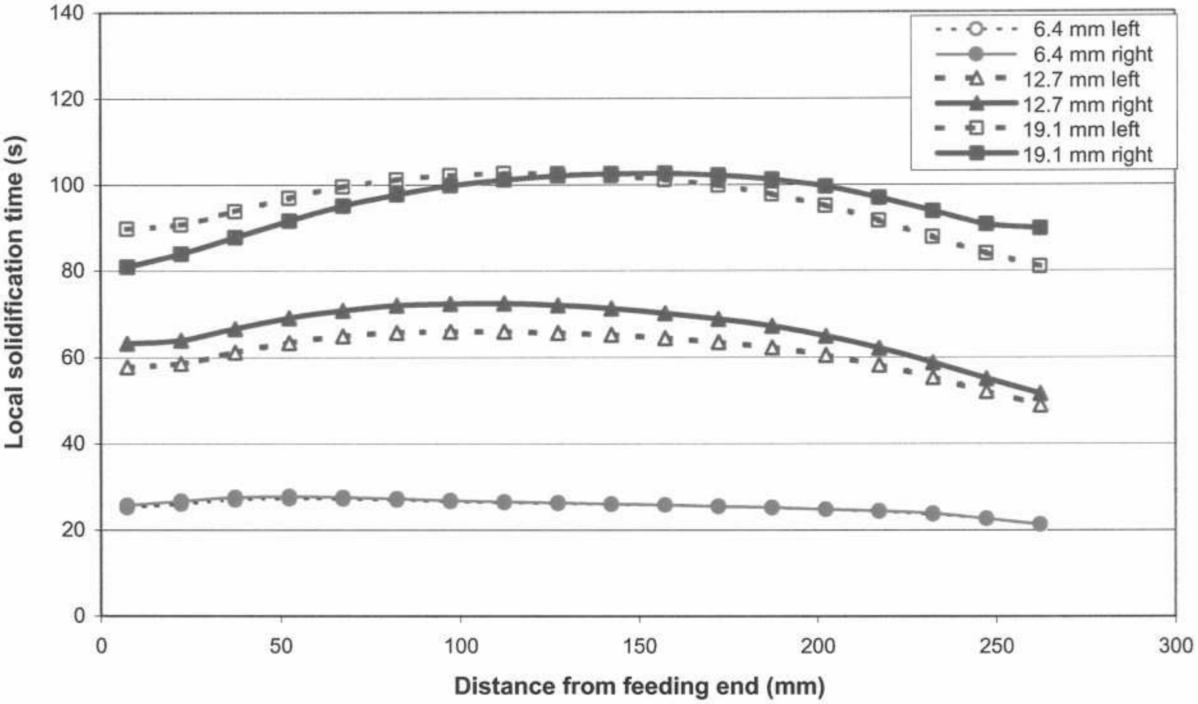


Fig. 7 Cooling rate (R) in different thickness plates for the 319 alloy

Determination of typical transformation temperatures

The typical transformation temperatures denoted as the solidus, liquidus and eutectic temperatures were examined by temperature measurements taken on the castings during solidification. The average values were calculated at the different locations (1, 2, 3, and 4 in Figure 4) from four plates. The results are given in Table 5. The values correspond to the typical transformation temperatures reported in the literature (Tenekedjiev et. al. 1995), this measured data was used to input the simulation model.

Table 5 Transformation temperatures used for data simulation

Temperature (°C)	$T_{liquidus}$	$T_{solidus}$	$T_{eutectic}$
319 with Sr	608.3	524.3	554.6

PREDICTION EVALUATION OF THE SINGLE THERMAL PARAMETER AND EXISTING CRITERIA FUNCTIONS

By correlating simulated thermal parameters (independent variables: X) to measured microporosity (dependent variable: Y) in plate samples, the regression equations can be established. Therefore, the goodness of the fit of the estimated equations, in other words, the effectiveness for single parameter and existing porosity criteria to predict microporosity (%), can be evaluated. The values of the **coefficient of determination (r^2)** show the percentage of variation of the microporosity in castings which can be explained by the thermal data. As a practical matter, for the typical data found in social sciences, values of r^2 as low as 0.25 are considered useful, while r^2 values of 0.60 or greater are rational in physical and life sciences (Anderson et al., 2001). For the complicated problem of predicting microporosity in castings, values of r^2 greater than 0.25 can be considered indicative, while values around 0.50 indicate that the criteria function may be used for prediction.

Table 6 shows the evaluation results corresponding to the single thickness data and the combined data. All of the results presented here were the best-fit ones selected from the five regression models (Table 3). It can be seen that the single thermal parameters (t_f, R, G, V_s) do have a strong effect on the microporosity formation, which is suggested by some of the r^2 values (0.28~ 0.68). The local solidification time (t_f) related to casting thickness appears more important than other parameters due to the higher values of r^2. Comparing the results for different thicknesses, the 19.1 mm thickness samples always have a higher correlation than those of 6.4 mm and 12.7 mm samples. This is probably due to the higher microporosity level in the 19.1 mm plates. Considering real castings with different cross-sections, the results based on the combined three thickness data indicate that single thermal parameters (t_f, G) may be used to predict microporosity in the castings with larger estimation errors, and the existing criteria functions (Niyama and LCC) cannot be used to predict microporosity in 319 castings due to the poor correlation.

Table 6 Evaluation of single parameter and existing criteria functions for the 319 alloy with different thicknesses

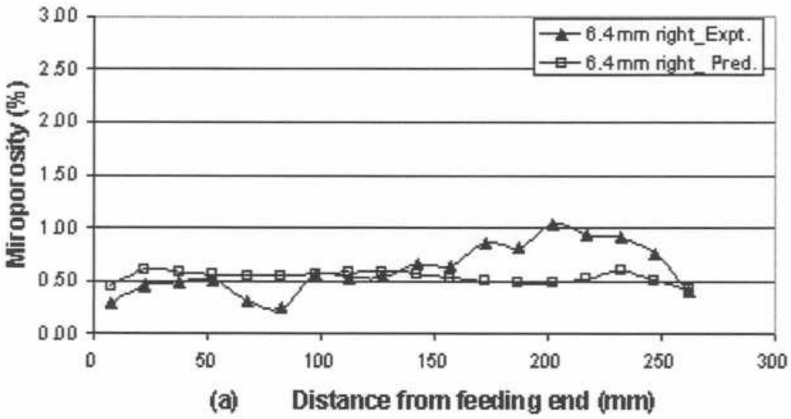
No.	Porosity criteria	Sample thickness	Coefficient of determination: r^2	
			Single thickness	**Three thickness combined**
1	**t_f**	6.4 mm	**0.52**	**0.47**
		12.7 mm	**0.38**	
		19.1 mm	**0.68**	
2	**R**	6.4 mm	0.11	**0.38**
		12.7 mm	0.01	
		19.1 mm	**0.33**	
3	**G**	6.4 mm	0.08	**0.47**
		12.7 mm	0.22	
		19.1 mm	**0.28**	
4	**V_s**	6.4 mm	**0.36**	0.21
		12.7 mm	0.09	
		19.1 mm	**0.53**	
5	**Niyama**	6.4 mm	0.16	0.02
		12.7 mm	0.21	
		19.1 mm	0.43	
6	**LCC**	6.4 mm	0.31	0.24
		12.7 mm	0.16	
		19.1 mm	0.41	

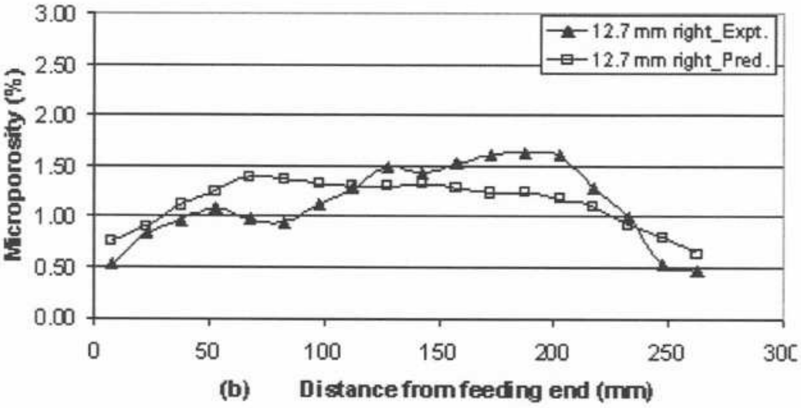
NEW CRITERIA FUNCTION

The method of multivariable regression analysis was used to develop a new criteria faction. Table 7 shows the results of multiple regression analysis using different regression models. An important fact that can be seen is that the values of r^2 in Table 7 are obviously greater than the results in the right hand column of Table 6. Thus the new combinations of thermal parameters provide a better prediction. Comparing the r^2 values and the number of variables with different models in Table 7, the best new criteria function was selected as $t_f^{1.98}R^{1.30}$ (The coefficients were determined from the regression calculation). Figure 8 displays the predicting results in different thickness plates using this new criteria function. The prediction errors are the distances between the predicted date lines and the experimental data lines, which are in the range of 0.01~ 0.55 %. The average error is 0.27 %. Again, the 19.1 mm thickness samples have lower errors.

Table 7 Results of multiple regression analysis for 319 alloy

No.	Regression model	r^2	No.	Regression model	r^2
1	$P = a \cdot t_f^b \cdot L^c$	0.53	6	$P = a \cdot t_f^b$	0.47
2	$P = a \cdot t_f^b \cdot R^c \cdot L^d$	0.56	7	**$P = a \cdot t_f^b \cdot R^c$**	**0.55**
3	$P = a \cdot t_f^b \cdot G^c \cdot L^d$	0.53	8	$P = a \cdot t_f^b \cdot G^c$	0.49
4	$P = a \cdot t_f^b \cdot V_s^c \cdot L^d$	0.54	9	$P = a \cdot t_f^b \cdot V_s^c$	0.53
5	$P = a \cdot t_f^b \cdot G^c \cdot R^d \cdot L^e$	0.56	10	$P = a \cdot t_f^b \cdot G^c \cdot R^d$	0.55





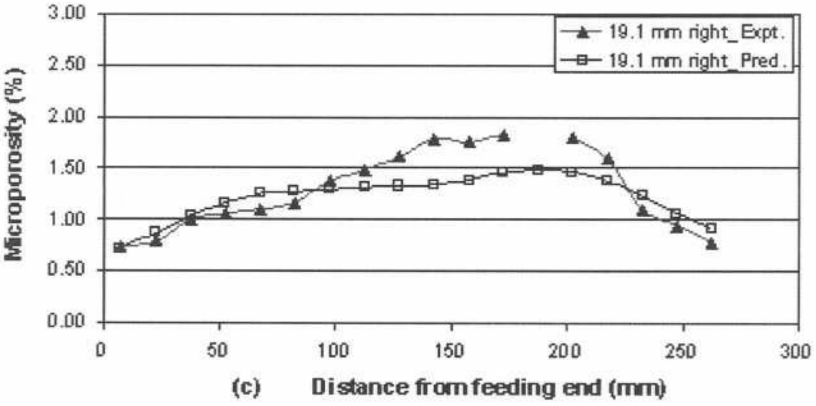


Fig.8 Microporosity prediction for different thickness plates using the new criteria function: $t_f^{1.98}R^{1.30}$

In order to validate this new criteria function, two new plate samples were randomly selected to obtain the real values of microporosity (%) which were then compared with the predicted values calculated using the new criteria function. Several specific locations were chosen, and the prediction errors were tabulated and given in Table 8. As can been observed, the prediction errors conform to the results shown in Figure 8 except at two locations on the left slice, 127.5 mm and 217.5 mm from feeding end. This greater error is probably due to macroshrinkage.

Table 8 Prediction errors using new criteria function: $t_f^{1.98}R^{1.30}$

Plate Thickness (mm)	**Position**	**Distance from feeding end (mm)**	**Prediction Error** $= \vert P_{predicted}$ **(%) -**$P_{neasured}$**(%)**		
			Left	**Right**	**Average**
6.4	G	97.5	0.10	0.05	0.07
	I	127.5	0.44	0.11	0.28
	K	157.5	0.28	0.17	0.23
	M	187.5	0.46	0.38	0.42
	O	217.5	0.42	0.34	0.38
	R	262.5	0.20	0.14	0.17
12.7	G	97.5	0.39	0.26	0.33
	I	127.5	**1.05**	0.10	0.57
	K	157.5	—	0.07	0.07
	M	187.5	—	0.19	0.19
	O	217.5	**0.59**	0.08	0.33
	R	262.5	0.23	0.24	0.24
19.1	G	97.5	0.19	0.09	0.14
	I	127.5	0.11	0.16	0.14
	K	157.5	0.49	0.32	0.40
	M	187.5	0.38	0.29	0.33
	O	217.5	0.08	0.08	0.08
	R	262.5	0.22	0.29	0.25
AVERGE			**0.29**	**0.19**	**0.26**

DISCUSSION OF ERROR SOURCES

The presence of error is inevitable for microporosity prediction using the criteria function method. This error results from different sources. The inherent drawback comes from the neglect of certain significant factors which influence microporosity formation, such as hydrogen content, alloy composition, and treatment of the liquid metal. In addition, another two factors related to the creation of criteria functions have to be considered. The first is the accuracy and abundance of data. To take this project as an example, the microporosity data were taken only from side slices of the plates. In addition there are some differences between the simulated and measured thermal data because solidification simulation is never perfect. If the data source were improved, it is believed that the new criteria functions would give more accurate predictions. In this particular case, to eliminate the macroshrinkage in the middle zone of the plates an improvement in die design would have allowed the amount of data to be increased by 33.3%. The calibration of the computer model with more abundant experimental data would also have led to an improvement in the quality of the simulated thermal data.

CONCLUSIONS

The thermal (solidification) parameters associated with the solidification process have a strong impact on the formation of microporosity in 319 Al-Si alloy since these factors determine the specific conditions for casting solidification. The local solidification time, which is related to casting thickness, is particularly important However, the single parameter method does not yield an accurate quantitative prediction.

Existing criteria functions, Niyama ($GR^{-1/2}$) and LCC ($Gt_f^{2/3}V_s^{-1}$), are not suitable for microporosity prediction in commonly used 319 Al-Si castings formed by the low pressure permanent mould process. This result confirms that the criteria function method is associated to specific casting conditions. The

Niyama criteria function has well accepted for porosity prediction in steels (Niyama et al., 1982), and the LCC criterion is highly correlated to microporosity in 356 alloy sand castings with a very low hydrogen condition (Lee et al., 1990).

A new criteria function, $t_f^{1.98}R^{1.30}$, has been developed by multiple regression analysis, which yields a better predicting result than the existing criteria functions.

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