Prediction of Microshrinkage Porosity in Thin Al-alloy Permanent Mold Castings

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Summary

The proper feeding conditions for thin Al-Alloy (AA336, JIS AC8A) castings in permanent mold were investigated to eliminate microshrinkage porosity. 5mm-thick plates (200mm long, 60mm wide) were cast with increasing padding taper from 0 to 5% under different conditions: (1) constant mold temperature of 350℃, (2) continuous production with uniform mold thickness (10mm), (3) continuous production with a negative taper of 2.5% in mold thickness (thickness decreasing in direction to riser).

The test casting were machined off to the midplane and the shrinkage porosity was examined visually. The critical padding taper which can just eliminate the shrinkage porosity was determined for each condition, i.e. : (1) 4.5% at the constant mold temperature, (2) 3.5% for continuous production with the uniform mold thickness (3) 1.5% for continuous production with the taper in mold thickness.

A computer simulation by a finite difference analysis program was applied to the test casting. The liquid fraction gradient (LFG) and the temperature gradient divided by the square root of the cooling rate (G/SR) were calculated at the end of solidification and compared with the shrinkage porosity area in the castings. For the case of constant mold temperature, LFG is a better parameter to predict shrinkage porosity than G/SR and its critical value is around 11%/㎝. But for the case of continuous production, neither LFG nor G/SR could be a reliable parameter.

The experimental results about the critical padding taper are of practical interest for designing permanent molds and castings. The computer simulation results stimulate further research to be directed on the prediction of centerline microshrinkage porosity in continuous production.

Zusammenfassung

Die geeigneten Speisungsbedingungen fur dünne Gußplatten aus Aluminiumlegierungen (AlSi12CuNiMg, JISAC8A) wurden in Kokillenguß untersucht, um die Schwindungsporosität zu beseitigen. 5mm-dicke Platten (200 mm lang, 60 mm breit) wurden mit zunehmender Keilverstärkung von 0 bis 5% unter verschiedenen Bedingungen gegossen: (1) Konstante Kokillentemperatur von 350℃, (2) nacheinanderfolgende Produktion mit gleichmäßiger Kokillenwandstärke (10 mm), (3) nacheinanderfolgende Produktion mit einer Keilverdünnung von

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2,5% in Kokillenstärke (in Speiserrichtung dünner werdende Dicke).

Die Gußplatte wurde bis zur Mitte bearbeitet und die Schwindungsporosität wurde visuell geprüft. Die kritische Schräge der Gußverstärkung, die gerade die Schwindungsporosität beseitigt, wurde fur die jeweilige Bedingung festgestellt. Sie war 4,5% bei der obigen Bedingung (1), 3,5% bei (2) und 1,5% bei (3).

Eine Komputersimulation mit einem FDM-Programm wurde für den Versuchsguß angewandt. Der Gradient des Restschmelzenanteils (LFG) und des Temperaturgradienten dividiert durch die Quadratwurzel der Abkühlungsgeschwindigkeit(G/SR)wurden am Ende der Erstarrung berechnet und mit dem Bereich der Schwindungsporosität im Gußstück verglichen. Für den fall von konstanter Kokillentemperatur ist LFG ein besseres Kriterium als G/SR um die Schwindungsporosität vorherzusagen und sein kritischer Wert ist ca. 11%/cm. Aber für den Fall von kontinuielicher produktion ist weder LFG noch G/SR ein zuverlässiges Kriterium.

Die Versuchsergebnisse über die kritische Schräge der Gußverstärkung sind für die Konstruktion von Kokillen und Gußstücken von praktischer Bedeutung. Die Komputersimulationsergebnisse erregen weitere Arbeiten für die Vorhersage der Mittellinienlunkerung in nacheinandergegossenen Guß stücken.

Résumé

Les conditions d'alimentation de moulage fin d'alliage d'aluminium (AA336, JIS AC8A) dans un moule permanent ont été examminées pour éliminer la porosité de retassure. Des plaques fines de 5 mm ont été coulées avce un effilé de coussinet augmentant de 0 á 5% sous diff'erenters conditions: (1) température constante du moule de 350℃ (2) produktion continue avce é paisseur uniforme du moule (10mm) (3) produktion continue avec un sffilé négatif (2,5%) dans l'épaisseur du moule (diminution de l'épaisseur en direction de la masselotte).

Le moulage de test a été usiné jusqu'á mi-plan et la porosité de retassure a été visuullement examinée. L'effilé du coussinet critique qui peut éliminer la porosité de retassure a été de 4,5% pour la condition (1) ci-dessus, 3,5% pour la condition (2) et 1,5% pour la condition (3).

La simulation sur ordinateur par FDM a été appliquée au moulage de test. Le gradient de fraction de liquide (LFD) et le gradient de température divisé par la racine carrée de la vitesse de refroidissement (G/SR) ont été calculés á la fin de la solidification. Les deux paramétres ont été comparés á la région de la porosité. Dans le cas de la température constante de moule, LFG est un paramétre meilleur que G/SR, et sa valeur critique est environ le 11%/cm. Mais dans le cas de la produktion continue, LFG et G/SR ne peuvent pas étre des paramétres de confiance.

Les résultats expérimentaux en ce qui concerne l'effilé du coussinet critique sont pratiquement intérssants pour les plans du moulage et du moule permanent. Les résultats de la simulation sur ordinateur stimulent des recherches supplémentaires dans la direction de la pré vision de retassure en milieu de ligne en production continue.

1. Introduction

The produktion of Al-alloy permanent mold castings is increasing along with the trend of weight reduction in vehicles. The casting wall thickness is tried to be kept at minimum to reduce the weight or the machining cost. The demand for higher quality makes the quality inspection specification ever harsher.

The microshrinkage porosity on the machined surface or in the castings like pistons and engine blocks is often unacceptable and makes the casting reject. The effect of a riser does not reach far in thin wall and it is uneconomic or often impossible to place many risers especially in permanent mold castings. A good way to prevent shrinkage porosity in this case is the padding of thin casting walls. Brinson and Duma [1] gave relations for the necessary padding taper in steel castings with wall thickness from 1/2 to 4 inches. No papers could be found, which dealt with the padding of thin walled Al-alloy permanent mold castings [2]-[4].

In this work, the necessary padding taper for a 5 mm thick plate cast horizontally in permanent mold is determined experimentally and the effect of the continuous production as in the foundry and the taper in mold thickness are investigated. The thin mold wall is heated faster but also cools faster. Therefore it is not obvious if the thin wall is favorable for reducing cooling rate in continuous foundry production.

AlSi12CuNiMg (AA336, JIS AC8A) alloy was chosen as the testing alloy because its solidification type is shellforming when modified with phosphor [5], [6] and tends to form centerline shrinkage porosity.

A computer simulation by a finite difference analysis program was applied to the test-casting. The temperature drop of melt during mold filling was necessary to be considered. The gradient of liquid fraction and the temperature gradient devided by the square root of cooling rate at the end of solidification were calculated and compared with the shrinkage porosity area as the criterion for the prediction of microshrinkage porosity along the centerline of the plate.

2. Experimental procedure

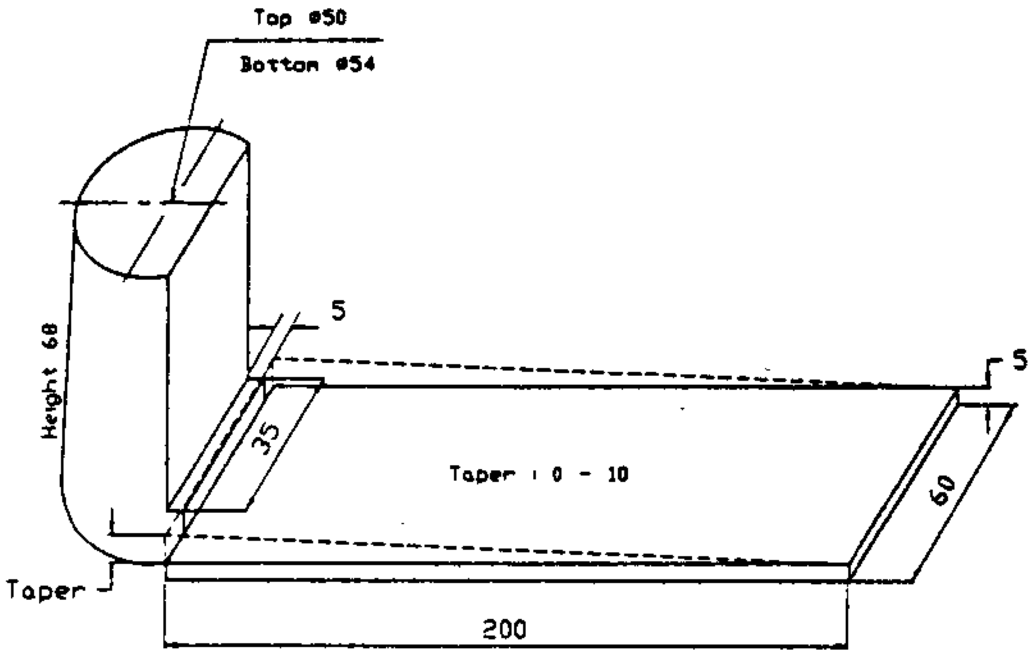

Figure 1. Test casting with various padding taper.

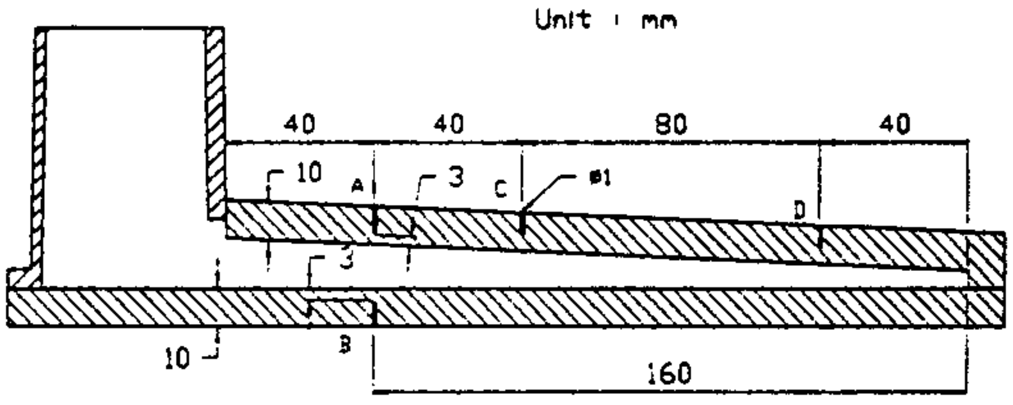

Figure 2. Permanent mold used and locations of thermocouples.

The test casting used to investigate the effect of taper of padding is shown in Figure 1. The upper mold plate was adjustable to change the taper from 0 to 5% (5 mm thickness increase in 100 mm length). The mold was coated with graphite base coatings and preheated uniformly in a furnace when necessary.

The mold thickness was 10 mm and made of steel. When testing the effect of the taper in mold thickness, the upper and lower mold plates were machined off to make the thickness decrease steadily to the direction of the riser. The mold temperature were measured with 1mmO.D. sheathed CA-thermocouples at the locations shown in Figure 2. The melt was poured through the riser to help the directional solidification.

The alloy AlSi12CuNiMg was prepared in an induction furnace to have the analysis of 12.7% Si, 1.2% Cu, 0.9% Mg, 1.1% Ni, 0.3% Fe and all other elements less than 0.05%. The melt was treated with phosphor-tablets and degassed with C_2Cl_6-containing degassing

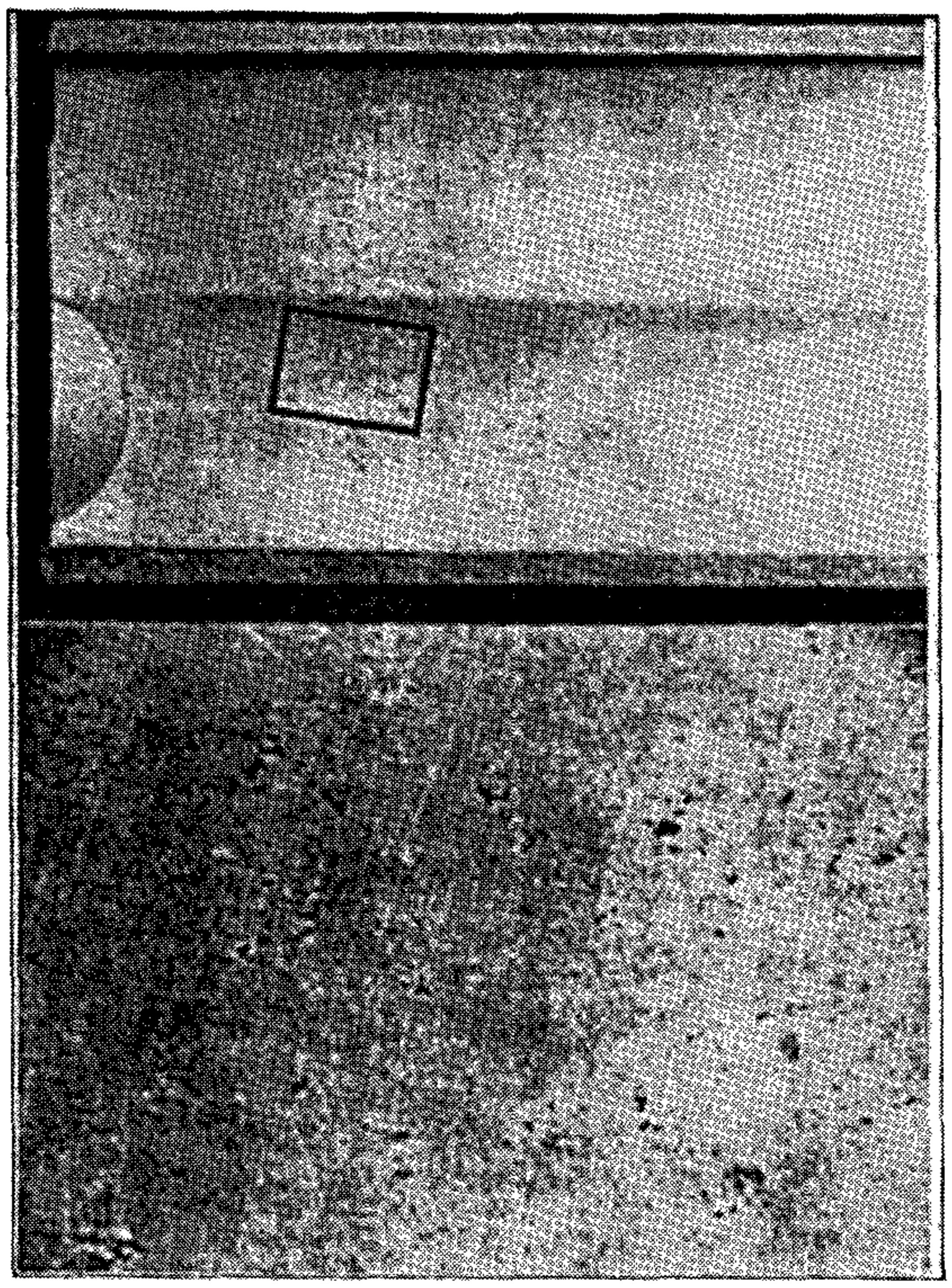

Figure 3. Photograph of shrinkage porosity at centerline of test casting, top : X 7/10, bottom : X 4.5, the part marked in the top picture is enlarged in the bottom.

tablets. It was then poured in small ingots to be remelted later for each test series. The pouring temperature was 750℃.

The shrinkage porosity in the test casting was examined visually by machining off the plate to the centerline. The porosity down to the pore size of 0.2 mm was well detectable as shown in Figure 3.

3. Experimental results

3.1 Critical padding taper at constant mold temperature

A series of test castings with padding taper of 0, 1, 2, 3, 4, and 5% were cast at constant mold temperature of 350℃. Figure 4 shows the shrinkage prosity of the test series. The test castings with padding taper up to 3% show evident shrinkage porosity while those above 4% exhibit no porosity. Another test series showed a slight porosity in the sample with 4% taper. It can be concluded that the critical padding taper is around 4.5% at the constant mold temperature of 350℃.

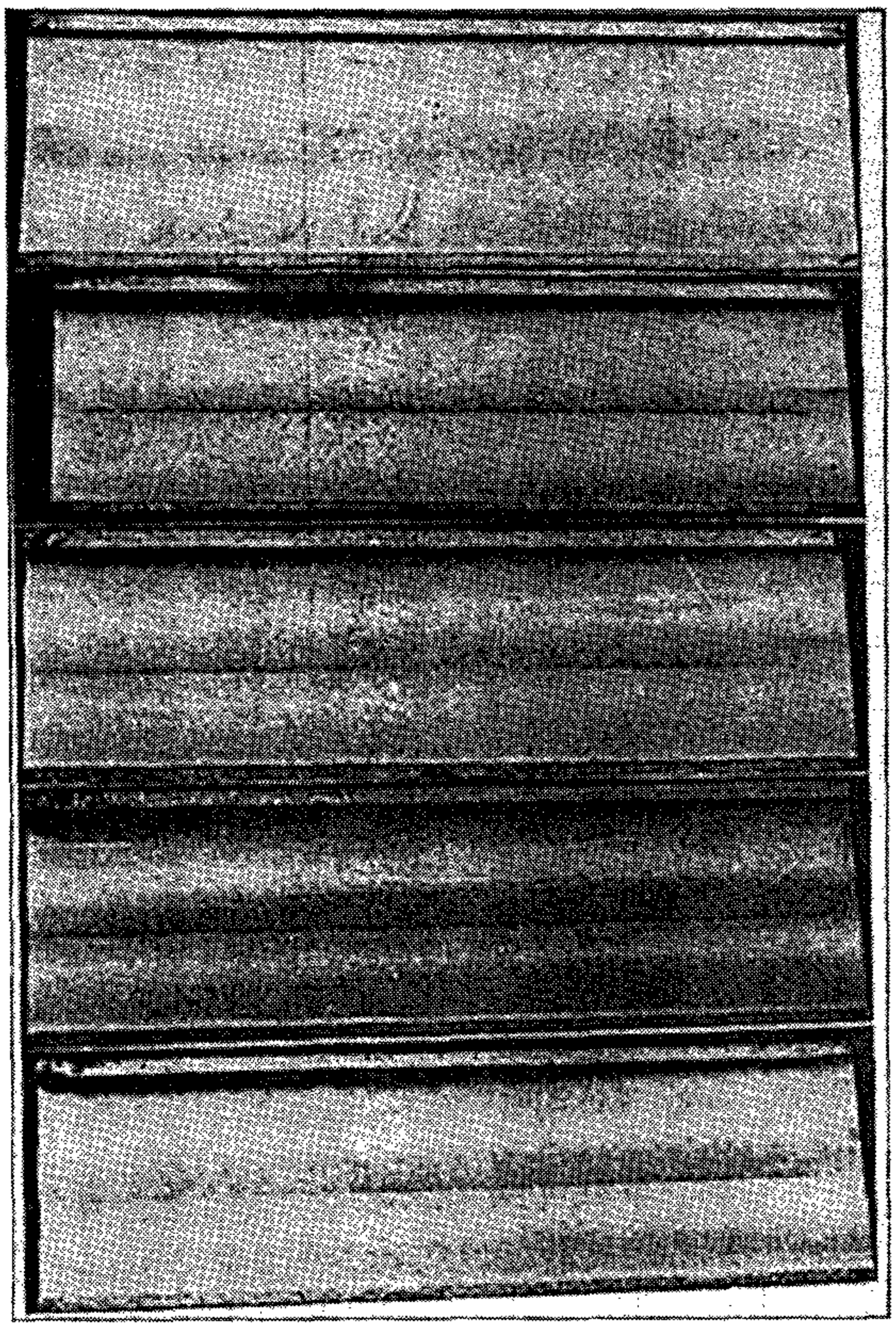

Figure 4. Photograph of centerline shrinkage porosity of test castings with different padding taper at constant mold temperature of 350℃ ; padding taper : 0,2,3,4,5% from top to bottom.

3.2 Critical padding taper in continuous production

The temperature distribution in permanent molds is not constant during actual production. It depends on metal to mold ratio, mold cooling, castings cycle etc. As in a production foundry, the test casting were made

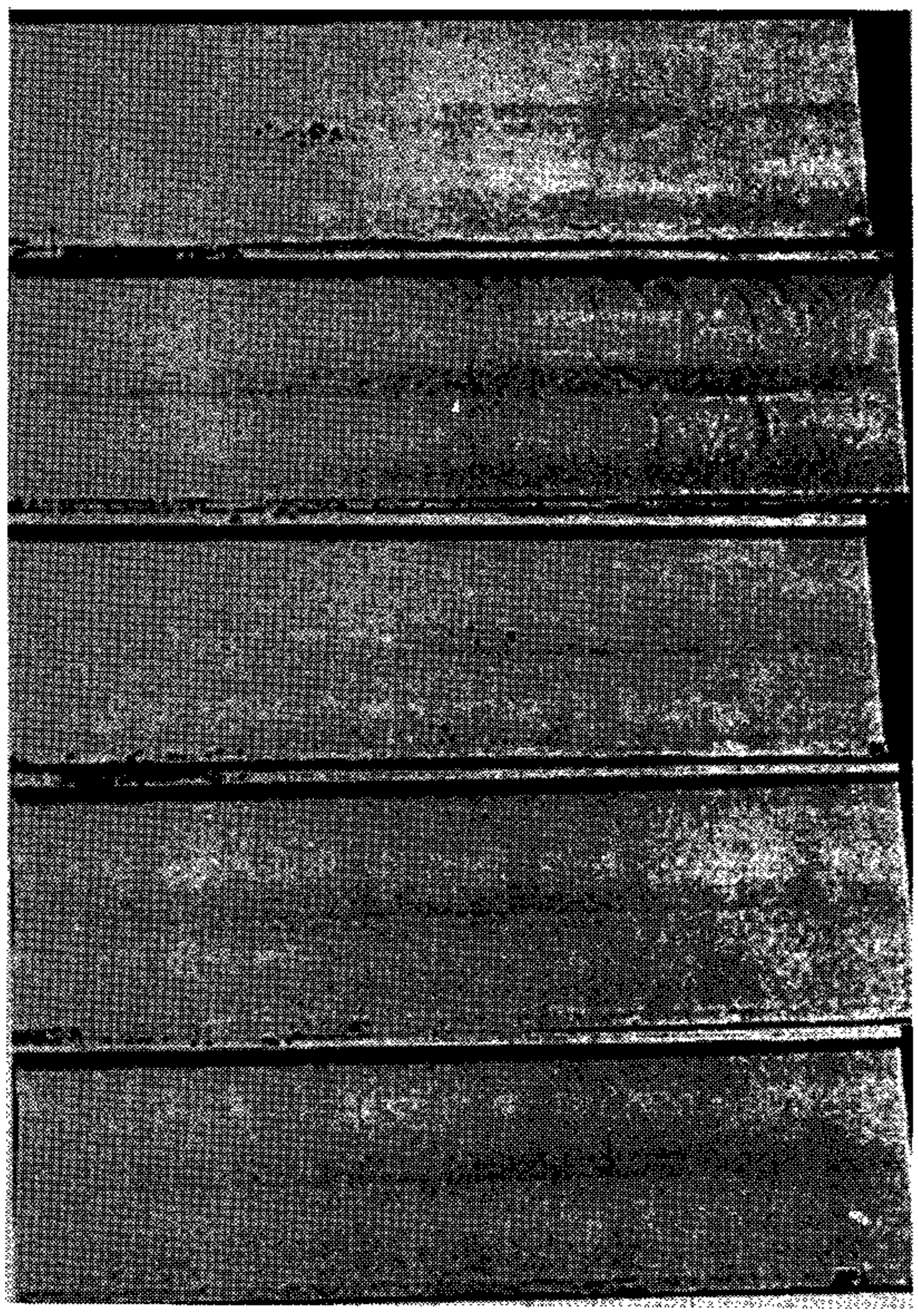

Figure 5. photograph of centerline shrinkage porosity of test castings with 3% padding taper produced consecutively : casting sequence from top to bottom.

out of the same mold one after another with a cycle time of around 330sec. Figure 5 shows the shrinkage porosity of the series with the padding taper of 3%. The severity of shrinkage porosity decreases with the number of casting poured and from the fifth casting on there are almost no porosity. With the padding taper of 4%, there was no porosity from the first casting on. Therefore the critical padding taper for the continuous production should be around 3.5%, compared to 4.5% at the constant mold temperature of 350℃.

3.3 Mold temperature variation during continuous production

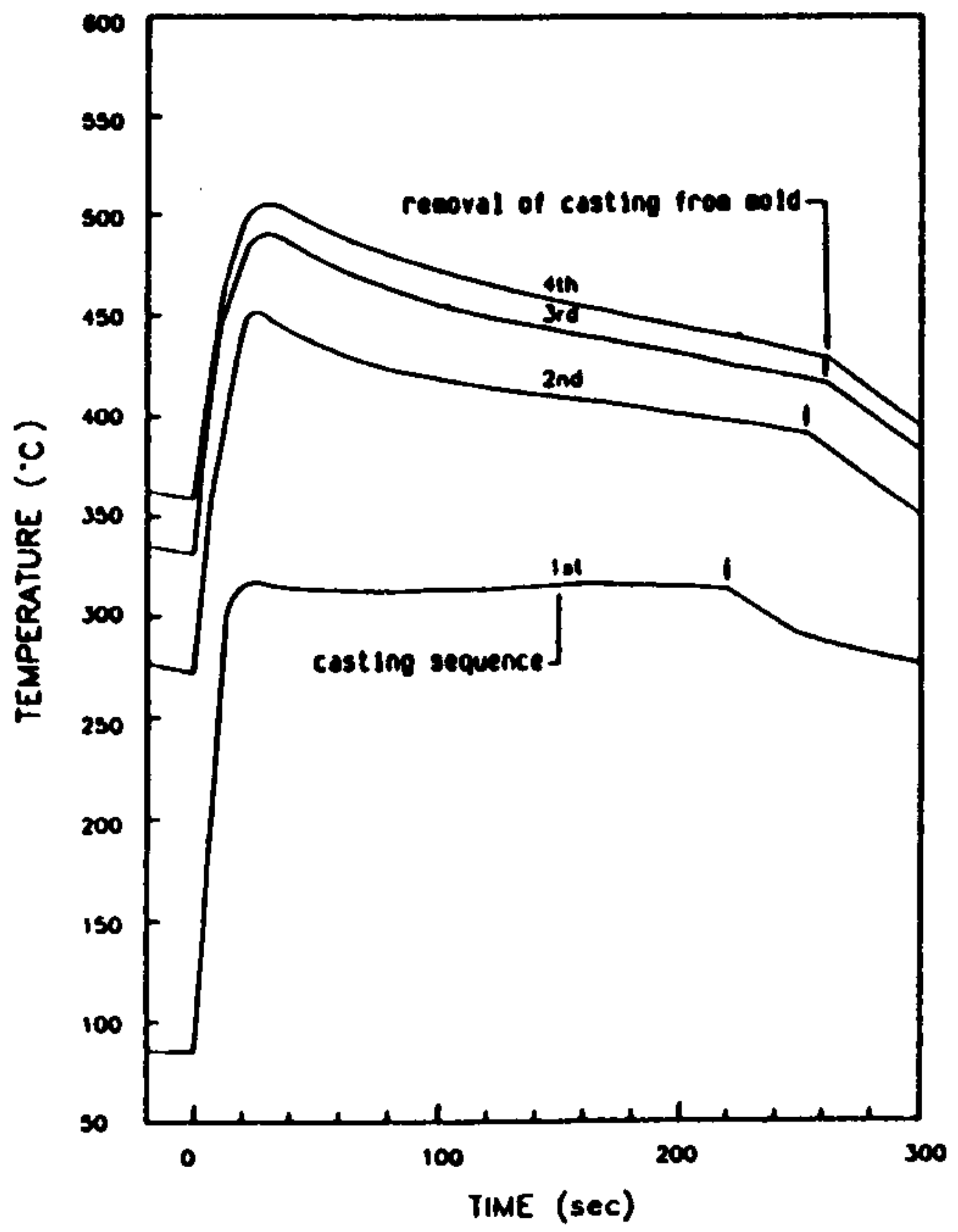

Figure 6. Temperature variation of mold at location A(Figure 2) from 1st to 4th casting with padding taper of 3%.

Figure 6 shows the temperature variation of the mold at location A(Figure 2) from the first to the fourth casting. The initial mold temperature was around 70℃ and after the first casting the mold was heated up to 300℃. After the 3rd casting the mold temperature change follows the same pattern and can be said to have reached the equilibrium stage.

The temperature variation of all 4 points of the mold in the equilibrium stage is shown in Figure 7. The temperature of the mold in contact with the thicker casting, is always higher than that with the thinner casting, improving the conditions for the directional solidification. This is the explanation why the critical padding taper is smaller in continuous production than that with constant mold temperature.

3.4 Effect of taper in mold

The taper in the mold was made to 2.5% (the mold thickness decreased by 2.5 mm in

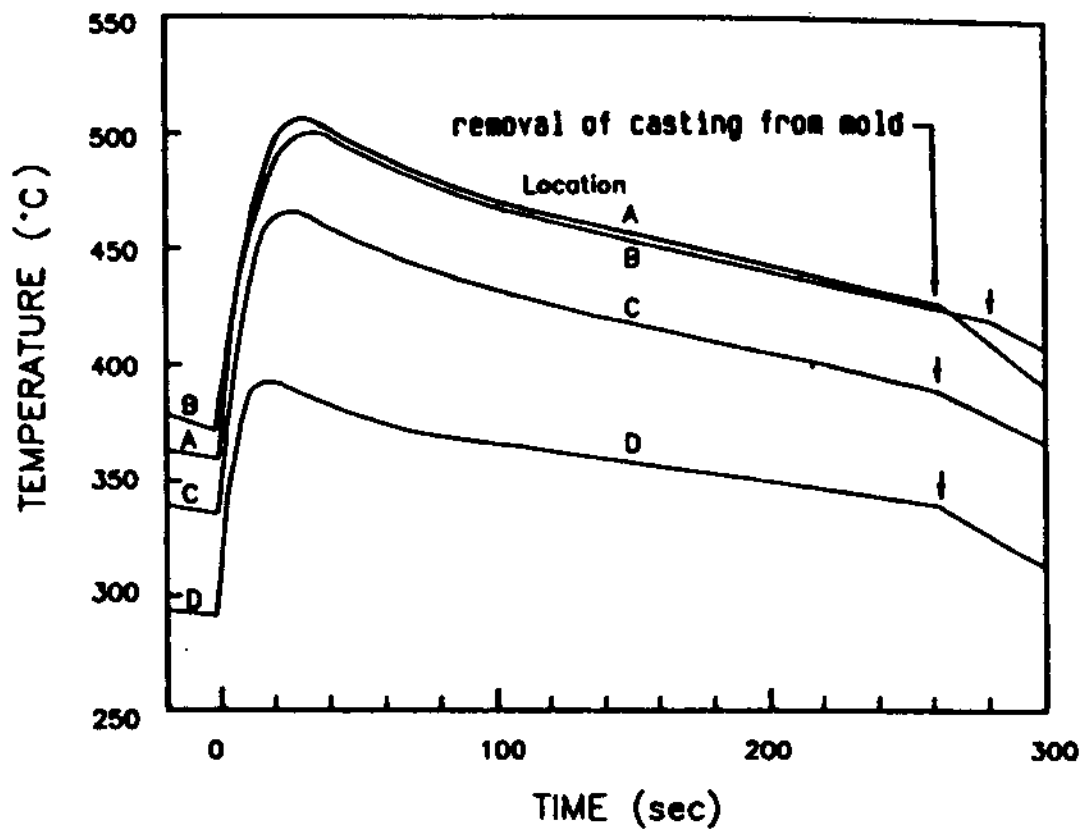

Figure 7. Mold temperature change at location A, B, C, D(Figure 2) during 4th casting with padding taper of 3%.

100 mm length to the direction to the riser.) Two series of test castings were cast continuously; one with a 3%-padding taper in casting and another with a 1.5%. Figure 8 shows the porosity in the casting with a 1.5%-padding taper. The first casting shows severe shrinkage porosity. The second and the third castings show slight porosity but the fourth one has no visible porosity. The other test series with a casting taper of 3% showed no porosity already from the third casting on. Therefore the critical padding taper in this case should be 1.5% or less, compared to 3.5% in the case with uniform mold thickness.

The temperature variations are compared in Figure 9 at locations A and D for the two molds: one with a mold taper of 2.5% and the other with a uniform thickness. The difference in the mold thickness at location A is 4 mm and the thinner mold is heated more repidly and to a higher temperature. This will retard the solidification rate in the thicker section of the casting. The difference in the mold thickness at D is 1 mm and the thinner mold is at higher temperature but not as much as at A. The cooling rate of the thinner mold is also greater but this does not affect the solidification of the casting as

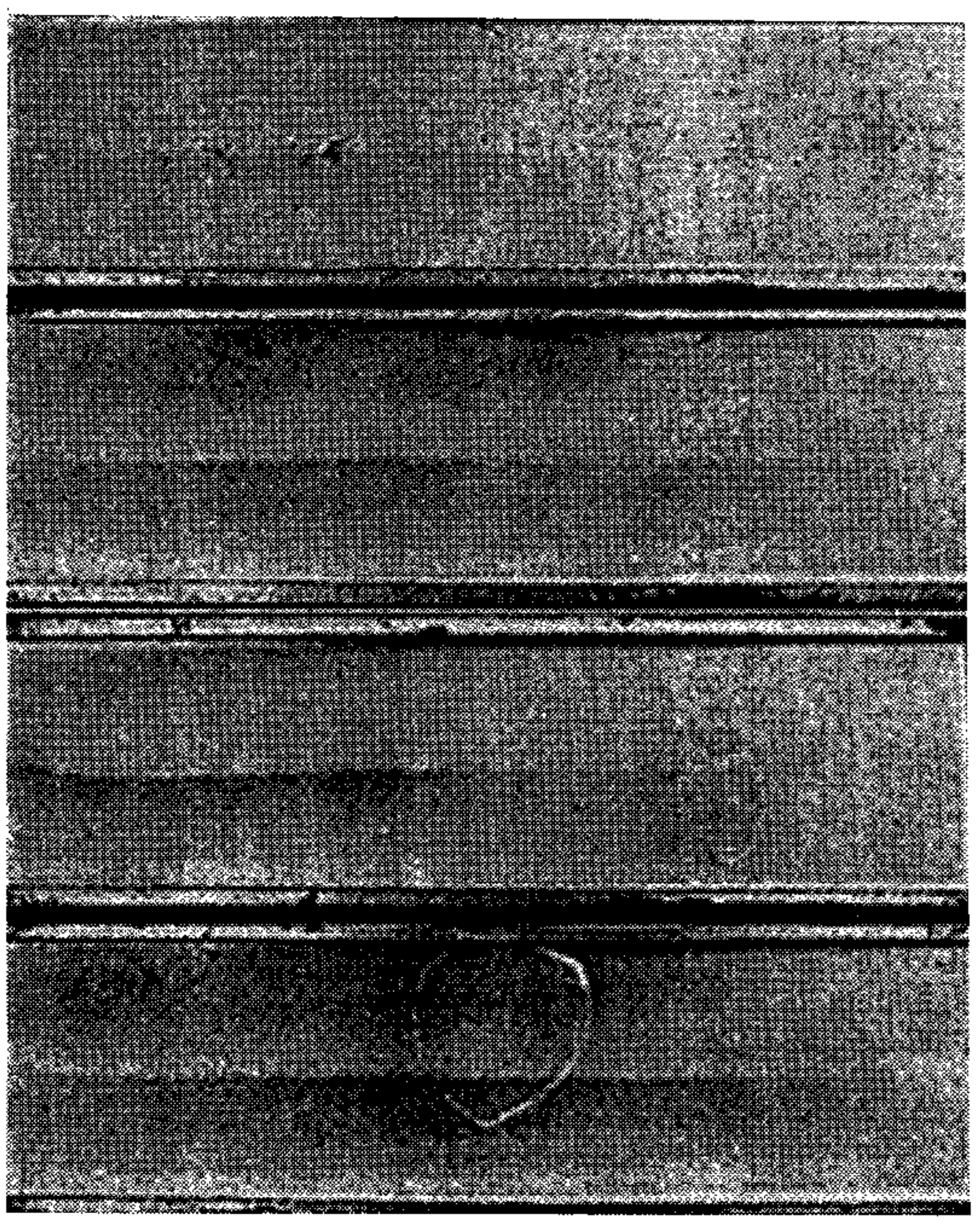

Figure 8. Photograph of centerline shrink- age porosity of test castings with 1.5% padding taper, cast consecu- tively in the mold with 2.5% taper in mold thickness, casting sequence from top to bottom.

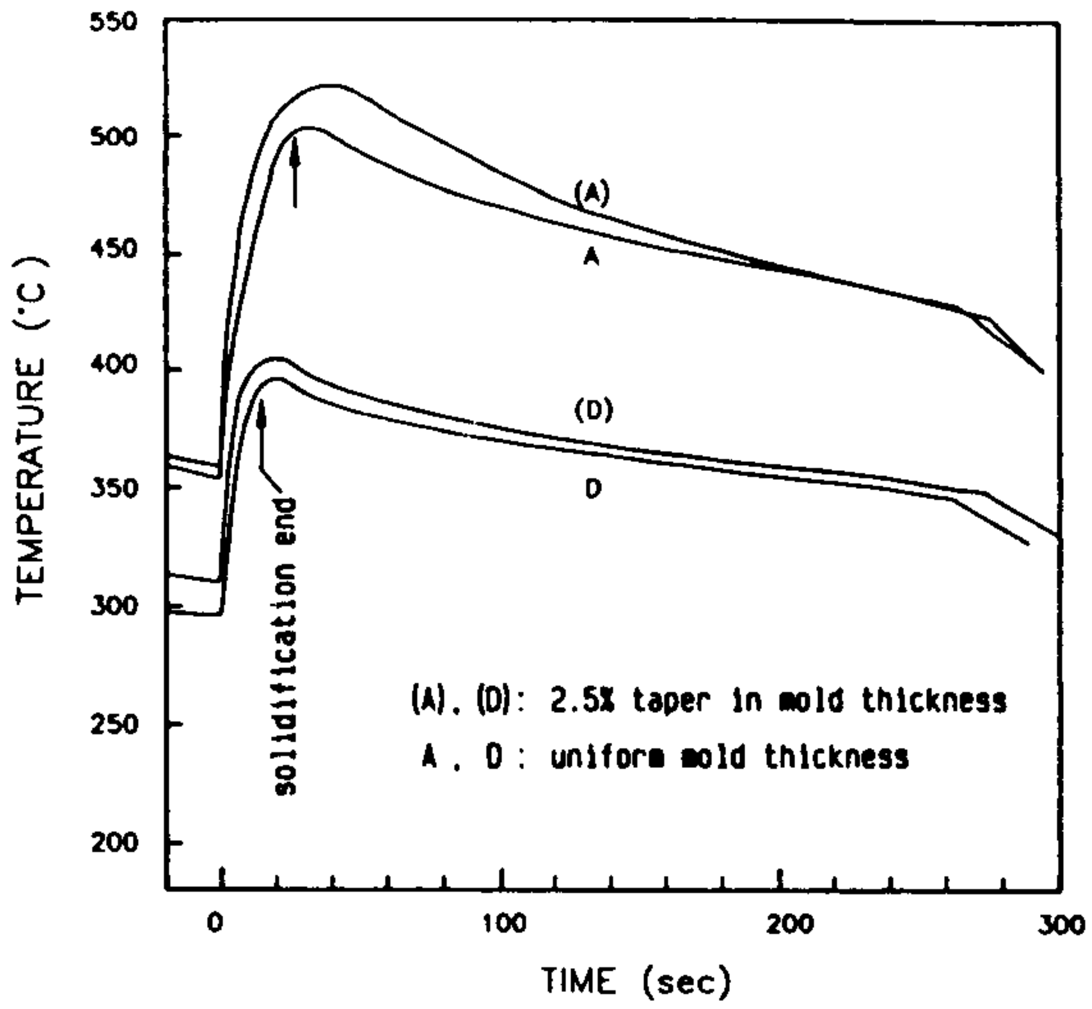

Figure 9. Effect of mold thickness on mold temperature variations at A and D; A, D: uniform thickness of 10mm (A), (D): mold with 2.5% taper, thickness st(A) and (D):6 and 9mm.

much as the faster heating because the cooling takes place after the solidification of the casting has finished. This explains how the taper in mold thickness improves the directional solidification and can reduce the critical padding taper of the casting.

4. Computer simulation

The experimental results about the critical padding taper can be useful for designing permanent molds and castings, But this application is rather limited to the cases similar to the experimental conditions. For a wider applicability, a computer simulation is applied for the test casting and the gradient of liquid fraction and the temperature gradient divided by the square root of cooling rate are tested as a parameter to predict the microshrinkage porosity along the centerline of the plate.

4. 1 Criterion to predict shrinkage porosity

There are many papers and commercial softwares for computer simulations [4], [16], [17]. But it still needs to be developed and refined to get a more accurate result, especially in permanent mold casting. Predicting shrinkage porosity in computer simulation requires a criterion. Serveral parameters were proposed as the criterion in the literatures, such as solidus temperature or equisolidification time contour line [7]-[9]; temperature gradient [10], temperature gradient divided by square root of cooling rate [11] at the end of solidification; gradient of solid fraction and critical solid fraction [12], [13]; pressure gradient method [14]. A critical value should be assigned to each parameters above which feeding is not any more possible and shrinkage porosity is supposed to form. The critical values of the parameters depend on the solidification type and the shape of castings. A method was proposed using shrinkage potential to determine the critical value of the parameters for different shape of steel castings [15].

In this paper, the gradient of liquid fraction along the centerline of the test casting was chosen as the parameter to predict the shrinkage porosity along the centerline. Some of the parameters mentioned above were not appropriate to predict the centerline shrinkage porosity in thin Al casting, because the contour lines of solidus temperature or critical solid fraction do not form a closed loop. The gradient of liquid fraction was calculated at the end of solidification. The greater the gradient of liquid fraction is, the better is the interdendritic feeding near the end of solidification. The interdendritic feeding ends before the end of solidification and it depends strongly on the solidification type[18]

In this paper, the gradient of liquid fraction at the end of solidification is compared with porosities in test castings. The temperature gradient G and the cooling rate R were also calculated to compare the parameters G and G/sqrt(R) at the same time.

4. 2 Computer simulation results

A finite difference analysis program was made with the consideration of heat transfer during mold filling and after casting removal. The melt was assumed to fill the mold step wise. The latent heat was assumed to be liberated uniformly in the solidification range from 560℃ to 550℃. A time step of 0.005 sec was used.

Figure 10 shows the melt peak temperature during pouring of the fourth casting in continuous production of the casting with 3% padding taper. The computed results are in good agreement with those of the experment. The temperature variations in the mold(location B in Figure 2) during the continuous production is shown in Figure 11. The cooling curve of the fourth casting is

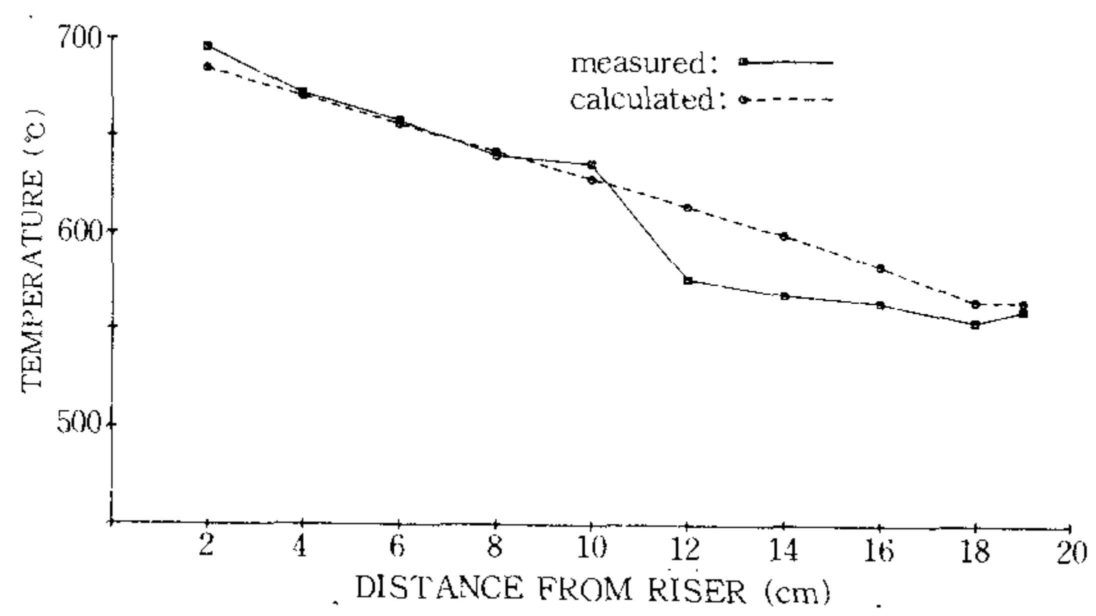

Figure 10. Measured peak temperature of melt in the mold during pouring and calculated temperature just after pouring the 4th casting with 3% padding taper.

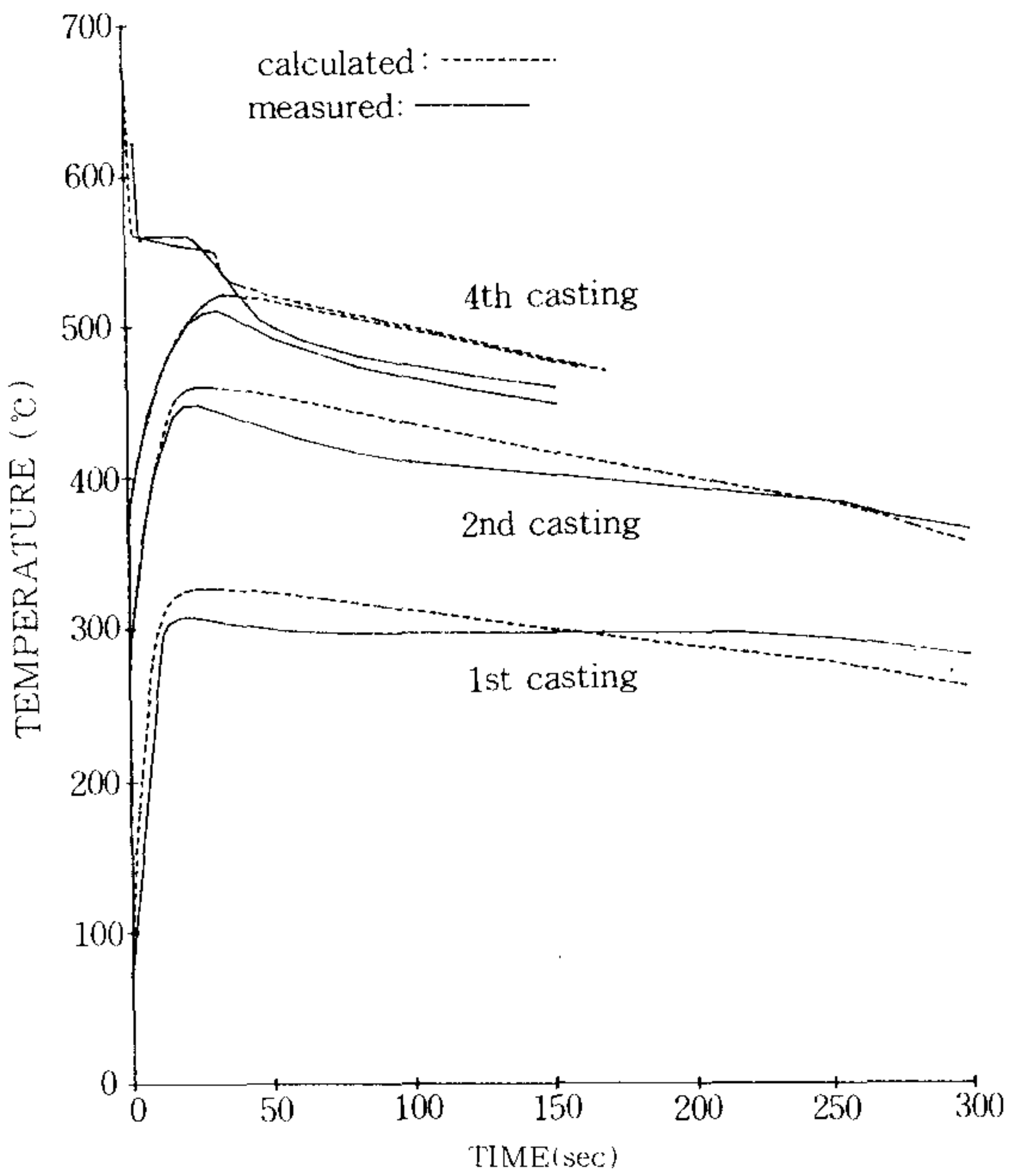

Figure 11. Measured and calculated mold temperature variation at B during 4 consecutive castings and the cooling curve of 4th casting at centerline above B.

also included. The computed results are relatively in good agreement with those of the experments. The computed temperature curves could not be exactly fitted to the experimental results because the heat transfer coefficients and the thermal properties of the materials were assumed to be constant, even though they change greatly during pouring and solidification[19]-[21].

Firure 12 shows the liquid fraction gradient (LFG) and the temperature gradient divided by the square root of the cooling rate (G/SR) at the end of solidification along the centerline of the casting for the test series with different padding tapers at the constant mold temperature of 350℃. The shrinkage porosity area is also marked comparing with Figure 4 and other test castings. The shrinkage porosity is formed approximately at the area where LFG is below 10 or 11%/cm. The correlation between G/SR and the porosity area cannot be well established. The temperature gradient at the end of solidification followed essentially the same pattern as the liquid fraction gradient, because the latent heat was assumed to be liberated uniformly over the solidification range. It is noteworthy that the minimum of LFG falls near the riser (4 to 6 cm from riser) and the minimum of G/SR near the end (2 cm from end).

Figure 13 shows LFG and G/SR for the castings with a padding taper of 3% pro-

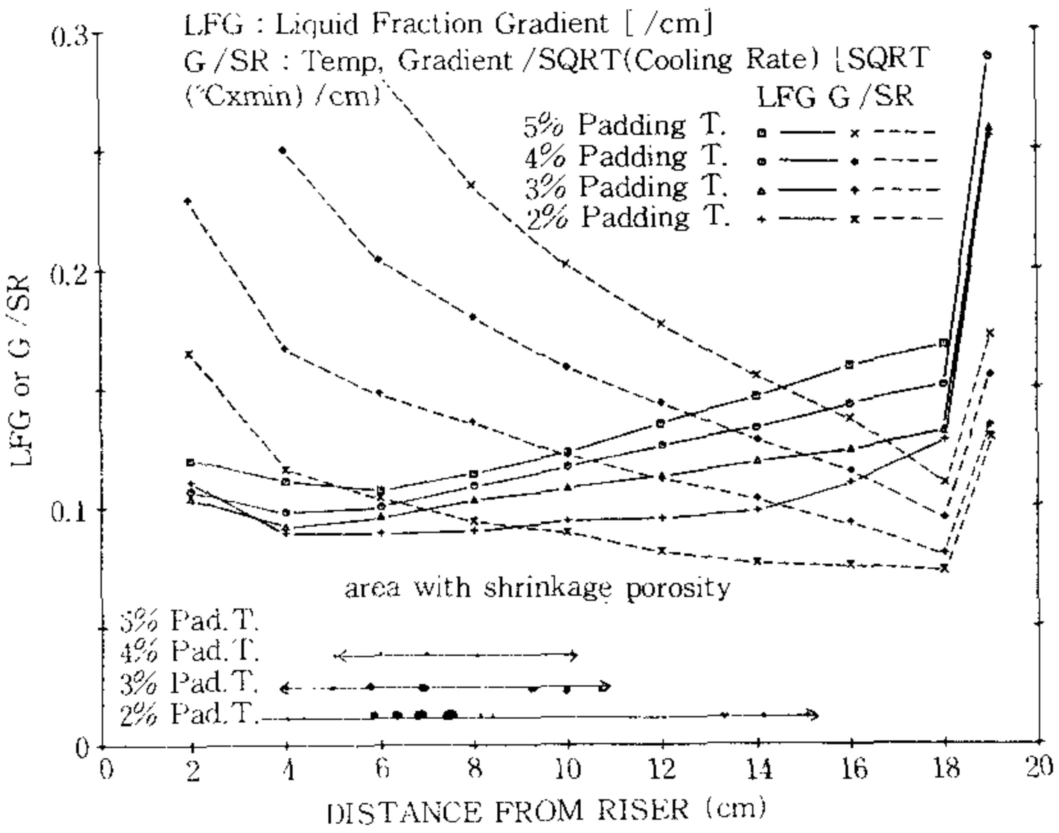

Figure 12. LFG and G/SR at the end of solidification along the centerline of the casting with different padding taper at constant mold temperature of 350℃.

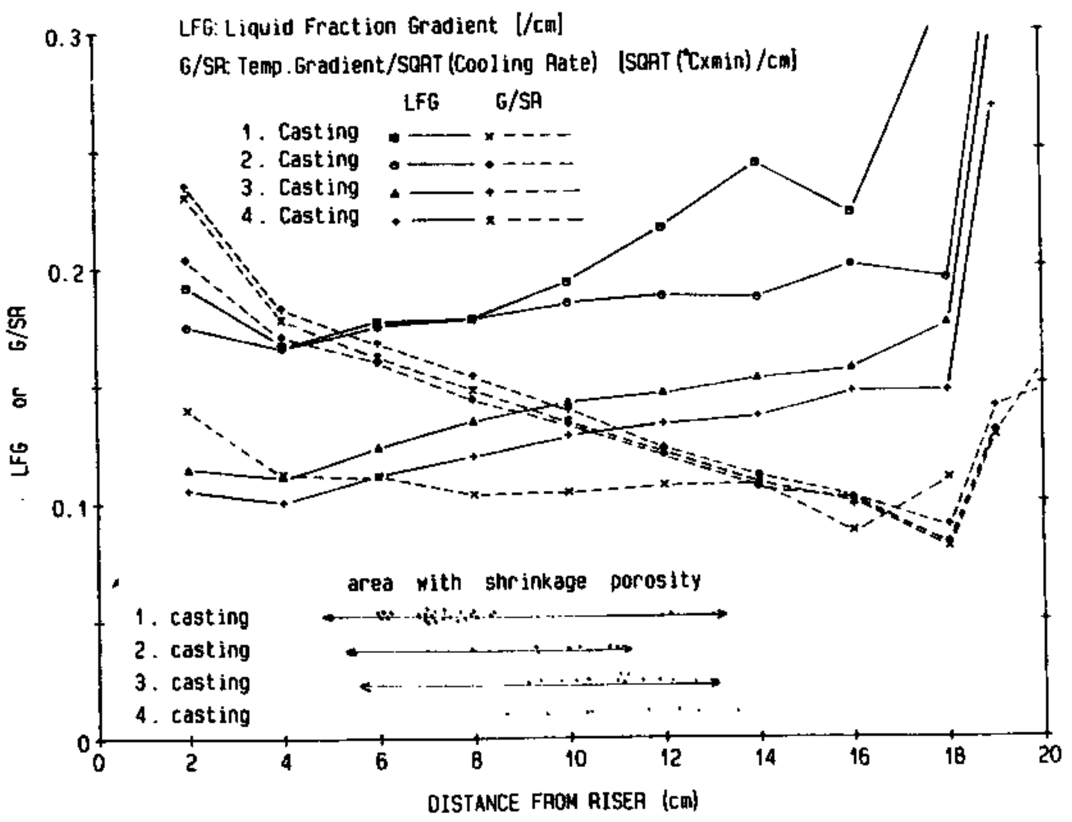

Figure 13. LFG and G/SR at the end of solidification along the centerline of 4 castings produced consecutively with 3% padding taper.

duced consecutively. The area of shrinkage porosity is also marked comparing with Figure 5 and other test castings. With increasing number of castings the LFG-curve moves downward, while the severity of shrinkage porosity decreases. The correlation between LFG and the porosity area cannot be established in this case. The correlation seems to exist rather between porosity area and G/SR, but it is diffcult to explain why the area with the lowest G/SR is free of porosity. Another consecutive casting series with a padding taper of 4% showed essentially similar LFG and G/SR-results, but the castings showed no porosity from the first casting on.

Therefore there are no reliable correlation between LFG or G/SR and the shrinkage porosity in continuous production.

5. Conclusion

For the practical benefit of permanent mold designers, the proper feeding conditions for thin Al-Alloy (JIS AC8A, AA336) castings in permanent mold were investigated to eliminate microshrinkaeg porosity. 5mm-thick plates (200 mm long, 60 mm wide) were cast with increasing padding taper from 0 to 5% under different conditions. The critical padding taper which can just eliminate the shrinkage porosity was determined for each casting condition, i.e.: (1) 4.5% at costant mold temperature of 350℃, (2) 3.5% for continuous production with uniform mold thickness of 10 mm, (3) 1.5% for continuous production with a negative taper of 2.5% in mold thickness.

A computer simulation by a finite difference analysis program was applied to the test castings. LFG (Liquid Fraction Gradient) and G/SR (temperature Gradient divided by Square root of cooling Rate) were calculated at the end of solidification and compared with the distribution of shrinkage porosity in the castings. It was found that LFG was a better parameter to predict the shrinkage porosity for the case of constant mold temperature than G/SR and its critical value was around 11%/cm. For the case of continuous production of permanent mold castings, neither LFG nor G/SR could be a consistently reliable parameter. Further study is necessary for this case.

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