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論　文
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Computer Simulation of Solidification Process in the Gravity Die Casting of Cast Iron

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주철의 중력금형주조에서 응고과정의 컴퓨터해석

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초　록

주철의 중력금형주조에서 반복작업에 따른 응고과정의 변화를 3차원의 수치해석적 방법에 의하여 컴퓨터해석을 하였다. 수치해석적 방법으로는 차분법을 채택하였다. 반복작업과정에 따라 변화되어지는 주물의 응고시간과 미세조직, 기계적성질과의 관계가 조사 되어졌다. 컴퓨터에 의해 계산된 각싸이클의 냉각속도로 부터 주물의 공정셀의 수, 경도, 인장강도등의 변화를 예측하였으며 또한 반복싸이클에 따른 금형 및 주물의 온도분포와 최종응고부위등을 예측하였고 이들은 실제주조시험에서 얻어진 결과와 비교적 잘일치하였다. 중력금형주조에서 회주철의 응고시간, 공정셀, 기계적성질 및 응고속도에 미치는 냉각수의 영향이 또한 컴퓨터해석에 의하여 잘예측되었으며 컴퓨터해석에 의한 냉각수 라인의 적절한 설계에 의하여 주물의 미세조직 및 기계적성질과 결함발생 가능위치를 효과적으로 제어할수 있음을 확인하였다.

1. Introduction

Permanent mold casting process of gray cast iron has several benifits of clean environment, high productivity, and high quality compared to sand mold casting. In permanent mold casting, active mold cooling systems are necessary to remove the heat of the solidifying metal. Thermal modeling is an important technique in designing of mold for improving the productivity of the process, for avoiding the formation of casting defects, and for increasing mechanical properties through regulating solidification rates.

Although heat flow designs in molds are commonly carried out by trial and error, this can be expensive in terms of lost time and mold modification costs. Several studies using computer simulation of die casting process have been reported. Grant[1] applied thermal modeling technique to a permanent mold casting cycle for improving the productivity of the process by using the two dimensional thermal modeling based on the FDM. Ikeda et al[2], studied a thermal analysis method to predict temperature distributions in a die casting. Recently Hong et al3). applied thermal modeling technique to a permanent mold casting for designing the cooling channel by using the BEM.

On the other hand, several studies on the prediction of mechanical properties and micro- structures have been reported. Makimura[4] applied thermal modeling technique based on the FEM to predict the

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microstructures and mechanical properties of cast iron in sand mold casting. Mampaey[5] has developed a simulation method that allows to calculate the eutectic cell count in lamellar graphite cast iron.

In this study, a basic three dimensional thermal model has been developed to simulate the solidification sequency for gravity die casting of gray iron. The finite difference method was used to model the solidification process during all the casting cycles. The effects of water cooling system on the die temperature, microstructure, and mechanical properties are also simulated.

2. Experimental procedures

Figure 1 shows the geometries of experimental castings. A simple shape of cast iron mold (GC 25) was used for eutectic gray cast iron castings (C : 3.3, Si : 2.8, Mn : 0.35). The numbers 1 and 2 indicate the location of thermocouples in the mold, and the letters A and B indicate the position of the water cooling channels.

With cooling channels, closed mold period is 30 sec and open mold period is 105 sec. With no cooling channels, closed mold period is 40 sec and open mold period is 105 sec. All
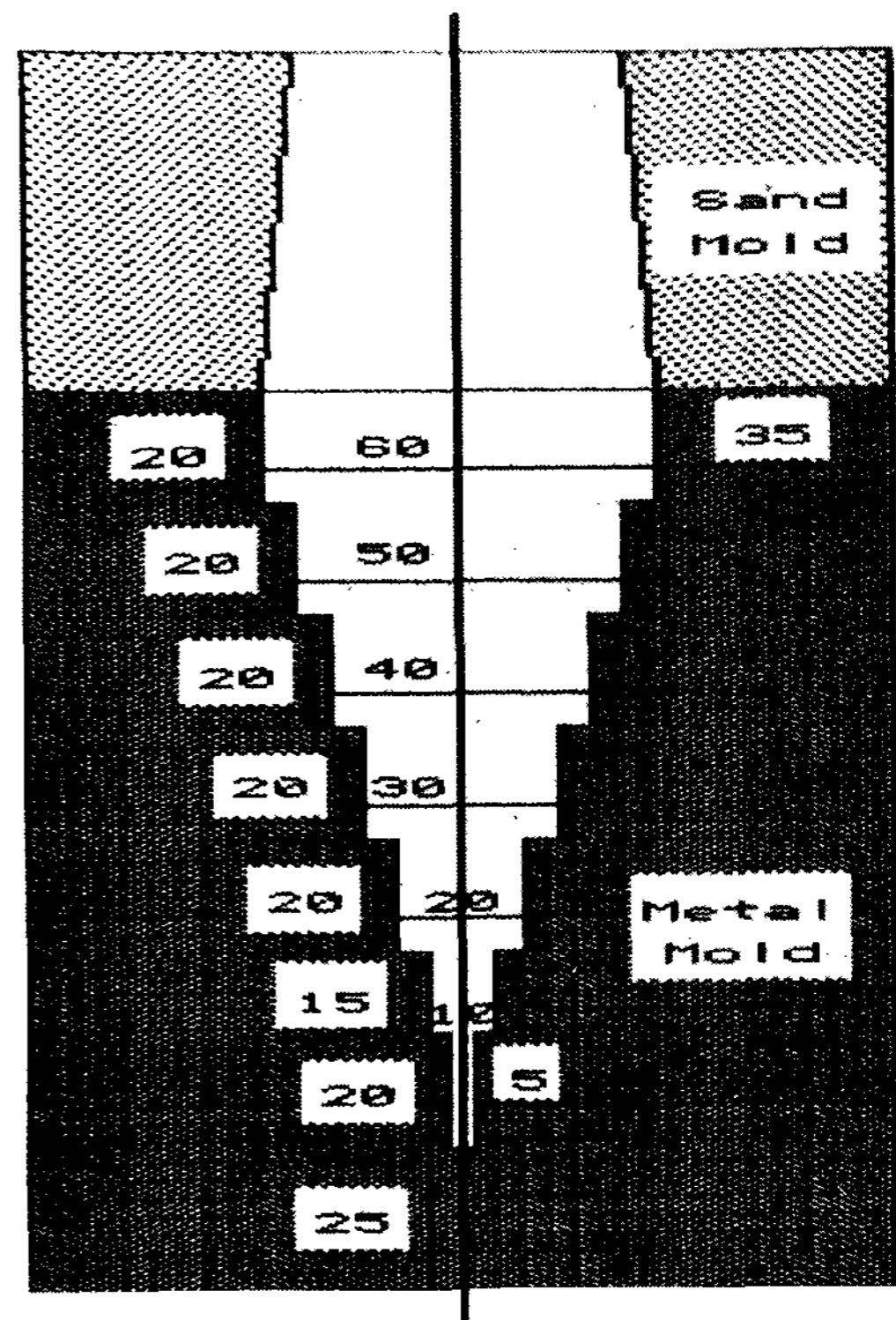

(b) Step casting. (Thickness : 150mm)

Fig. 1. Geometry of experimental castings.

the castings were annealed at 900℃ for 2hr and cooled in a furnace to have a full ferritic matrix. Molten cast iron was poured at 1300℃

3. Numerical Modeling

A three dimensional thermal model based on the FDM was used to simulate the solidification process of the casting/mold system. An instant fill of the molten metal into the mold cavity was assumed at the start of the closed mold period. During the open mold period, casting is removed from the mold and interface of casting/mold is converted to interface of air/mold, then boundary condition is changed.

In the cyclic casting process, during the closed mold period both the solidification and
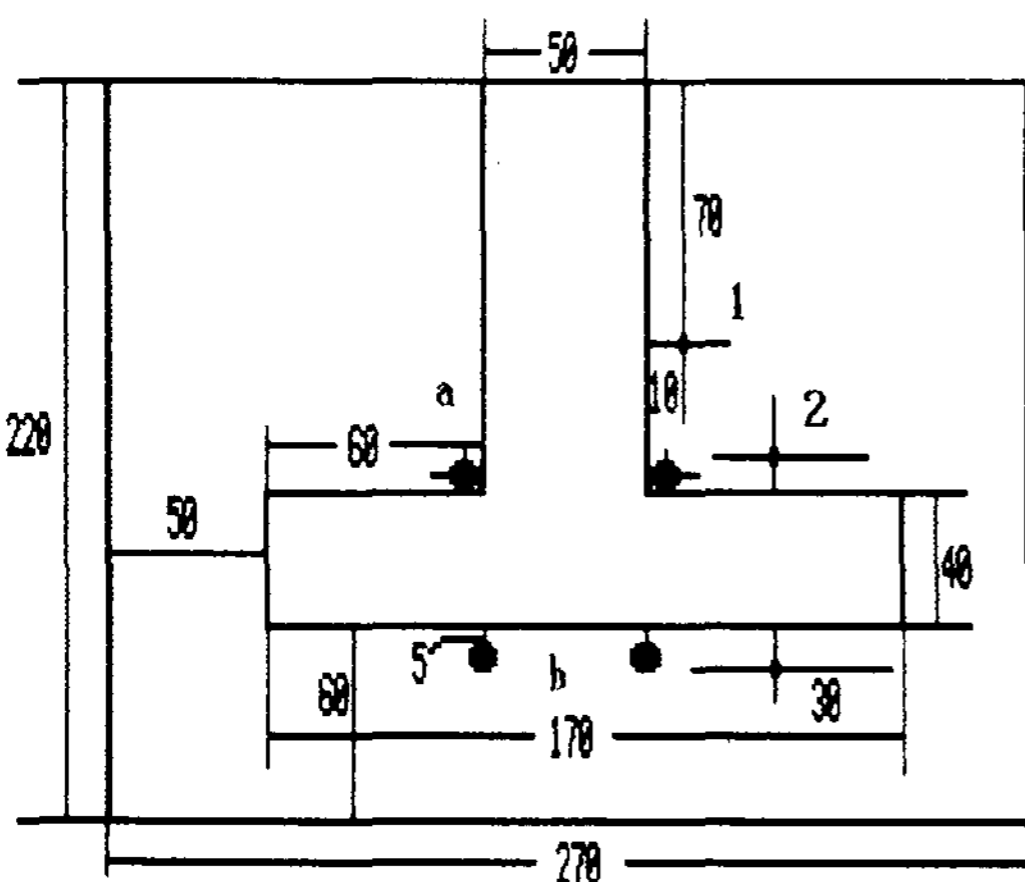
(a) T shape casting. (Thickness : 20mm)

temperature distributions in casting and mold are analyzed. However, during the open mold period only the heat flow problem in mold is necessary to be analyzed.

4. Results and Discussion

Heat flow analysis in metal mold during cyclic casting process

Accurate control of thermal history in mold during cyclic casting are very important in the gravity die casting process since productivity and quality of products are closely affected by the thermal history.

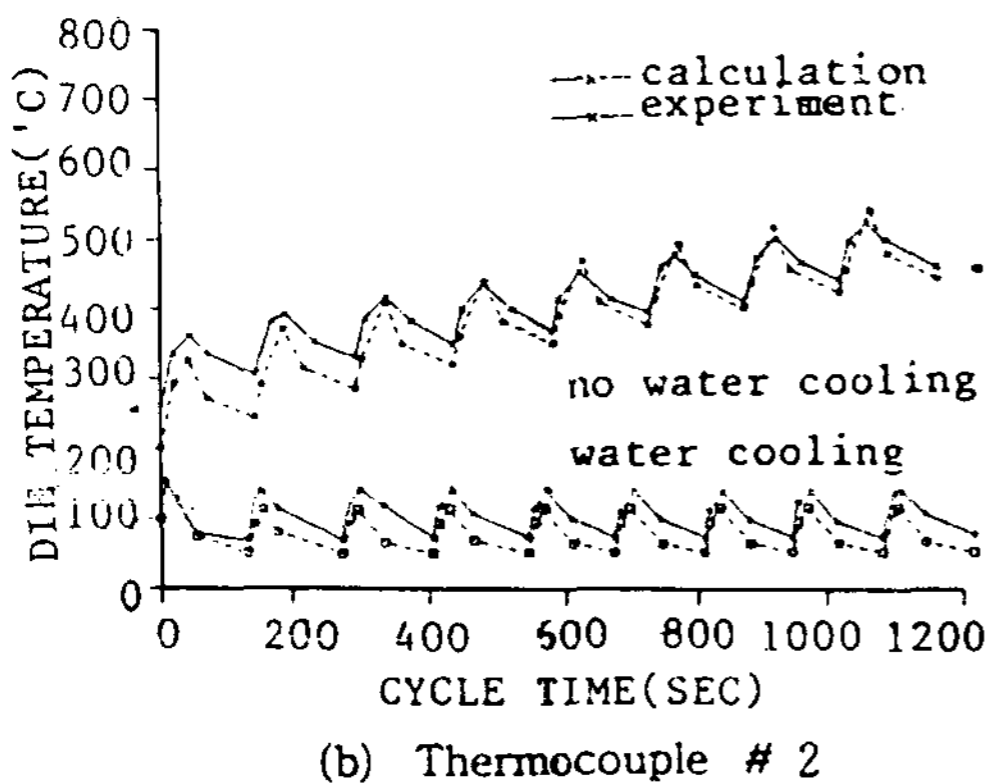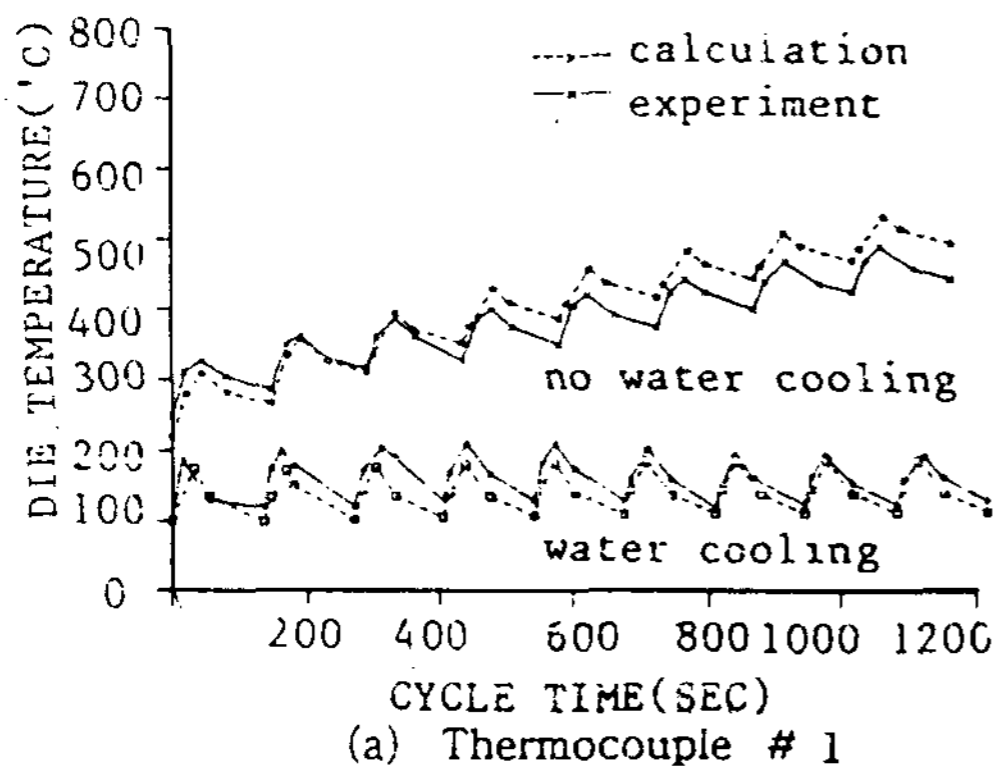Measured and calculated thermal histories for several nodes in metal mold are shown in Figure 2 ⟨a⟩ and ⟨b⟩. It can be shown from the figures that temperature profiles are not changed by cycling in the case of water cooling. So it is possible to control the thermal histroy in mold during cyclic casting process by using the water cooling system.

Figure 3 shows the contour lines of solidification time in casting cycle 3 through 9; (a) for with water cooling, and (b) for without water cooling channels. As shown in the figures, solidification patterns are not affected by cycling in case of water cooling.
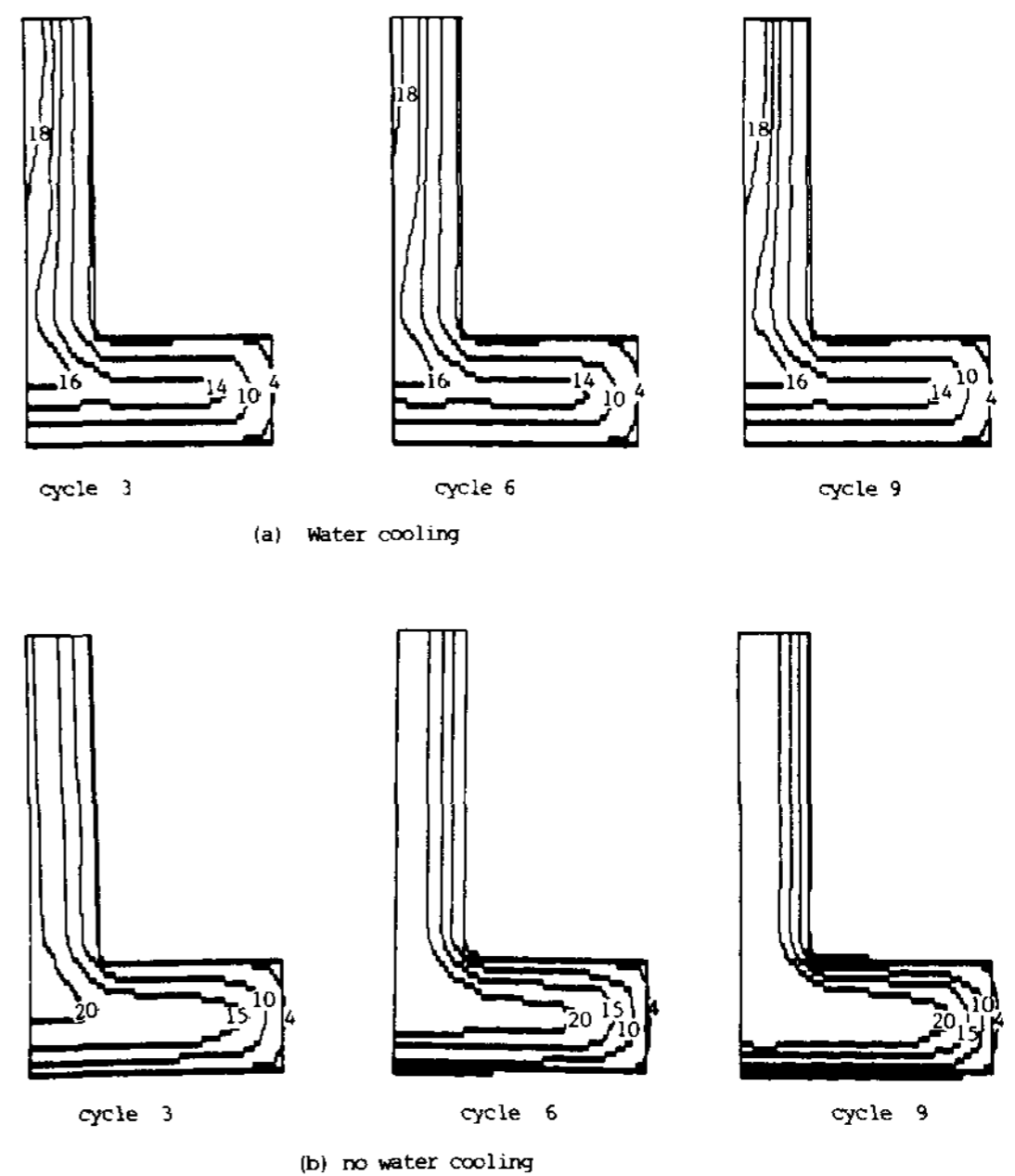

Fig. 3. Contour lines of solidification time. (unit : sec)

Relationship between eutectic solidification time and microstructure, and mechanical properties in step castings

In general, the microstructure and mechanical properties of solidified materials are closely related to the cooling rate and solidification time. In order to examine the effect of eutectic solidification time of gray cast iron on the number of eutectic cells and mechanical properties, experimental castings with various thickness were used.

Fig. 2. Thermal history of mold during cyclic castings.

Figure 4 shows the contour lines of calculated eutectic solidification time in step casting. The relationship between the calculated eutectic solidification time(t_E) and measured number of eutectic cells (N_{EC}) is illustrated in Figure 5. From the figure, the following relation can be obtained by regression analysis.

$$N_{EC}=4669.5 \times t_E^{-0.6}$$

Figure 6 shows the relationship between the calculated eutectic solidification time and hardness(H_{RB}), and a similar relation can also be obtained as follows;

$$H_{RB}=128.8 \times t_E^{-0.26}$$

Figure 7 illustrates the relationship between the calculated eutectic solidification time and tensile strength(UTS), and in a similar procedure the following relation can be obtained.
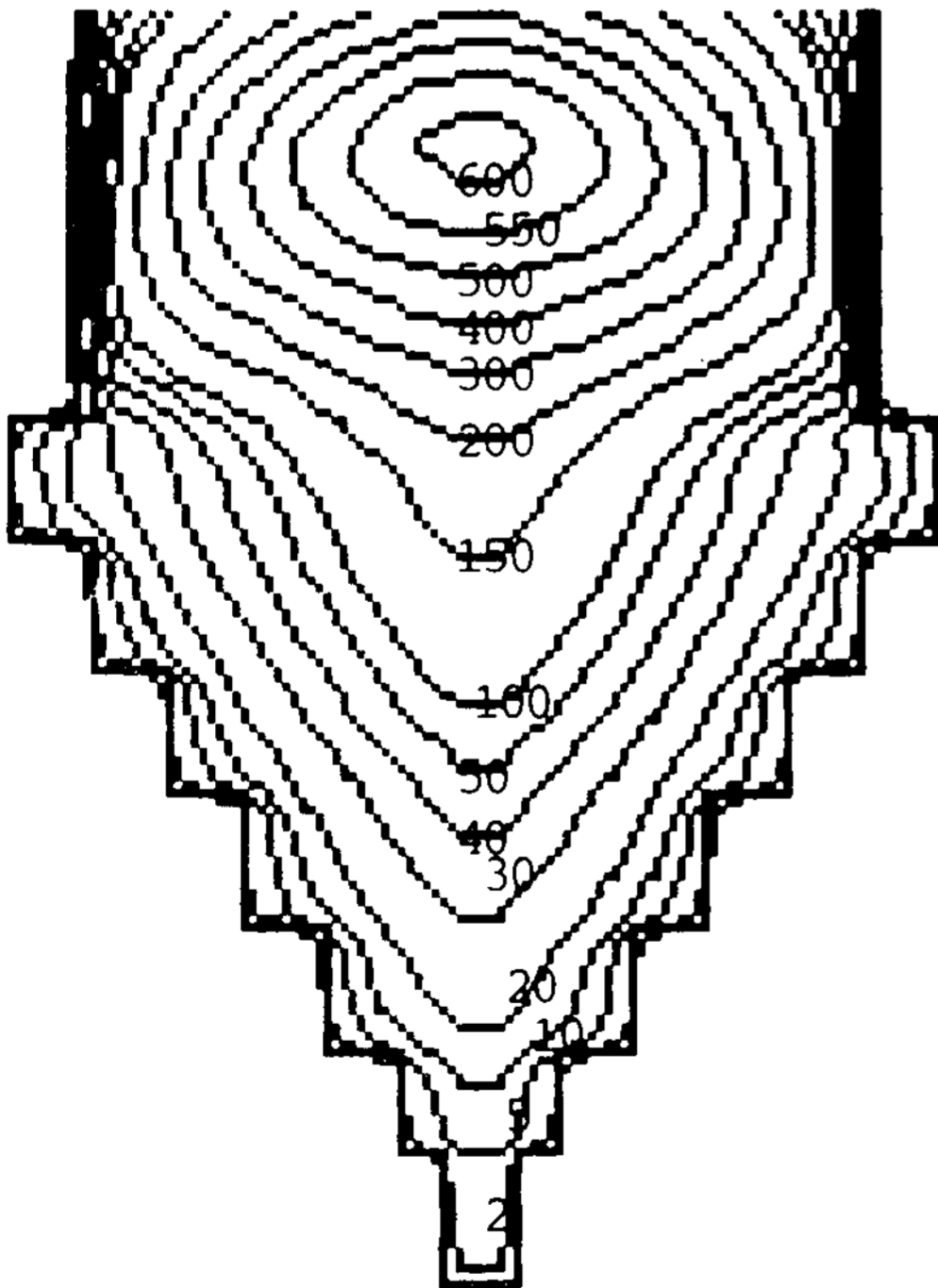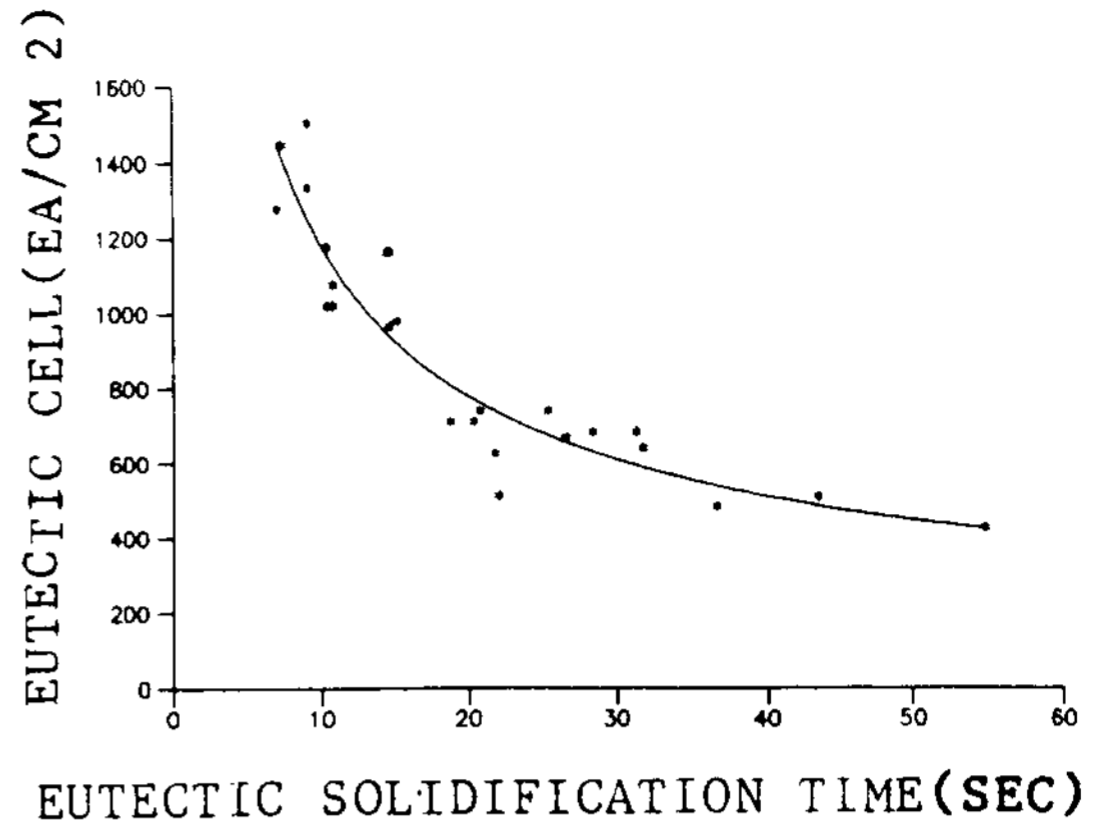
$$UTS=94.46 \times t_E^{-0.53}$$

Fig. 5. Relationship between the number of eutectic cells and calculated eutectic solidification time.
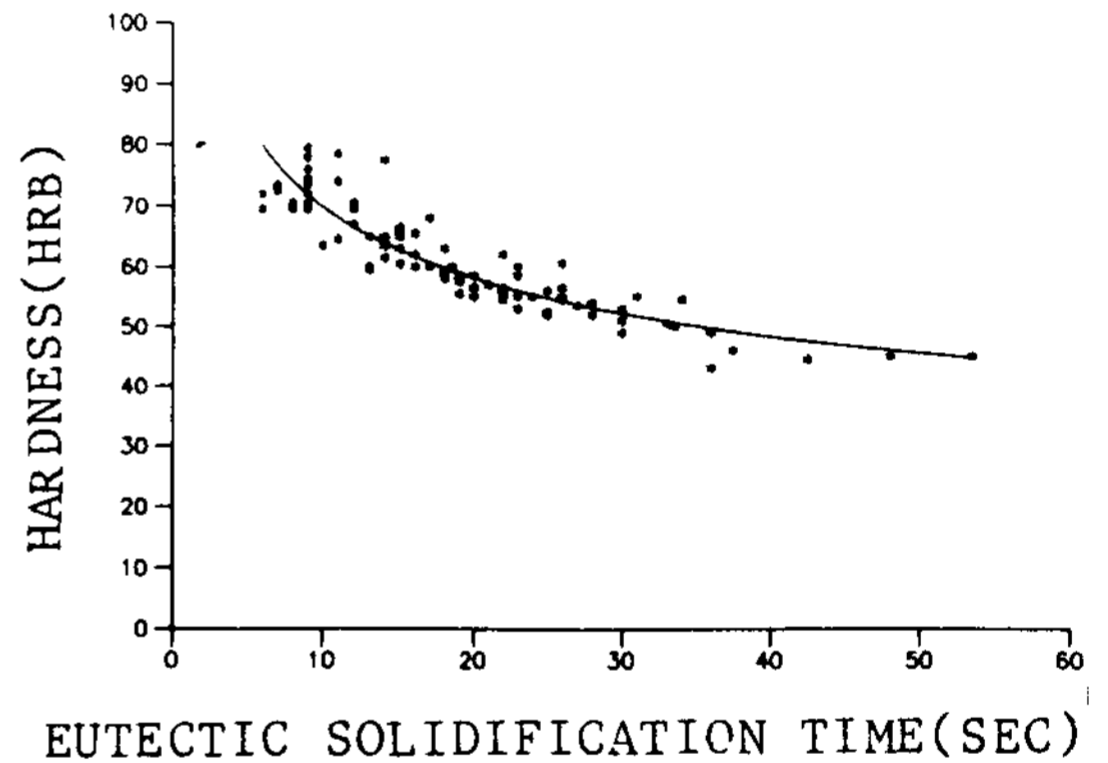

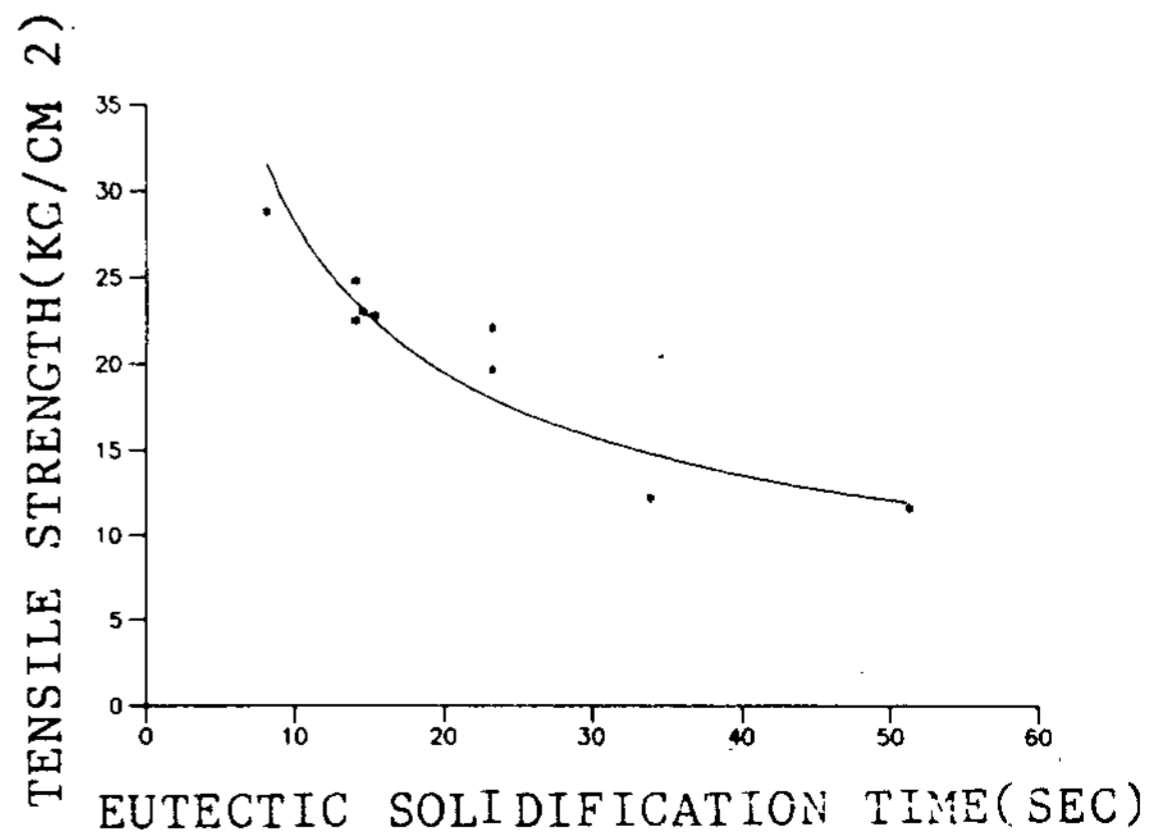Fig. 6. Relationship between hardness and calculated eutectic solidification time.

Fig. 7. Relationship between tensile strength and calculated eutectic solidification time.

Fig. 4. Contour lines of solidification time in step casting. (unit : sec)

Prediction of microstructure and mechanical properties of T shape casting in cyclic casting process

The variation of eutectic solidification time with cyclic casting is shown in Figure 8. As shown in the figure, without water cooling, eutectic solidification time increases with cycling, however, with water cooling, no variation of solidification time is found. The relationship between the calculated number of eutectic cells and the casting cycle is shown in Figure 9. The effect of water cooling on the number of eutectic cells can be seen in the figure.

Figure 10 illustrates the effect of water cooling on the hardness during cyclic casting. And the effect of water cooling on the ten-
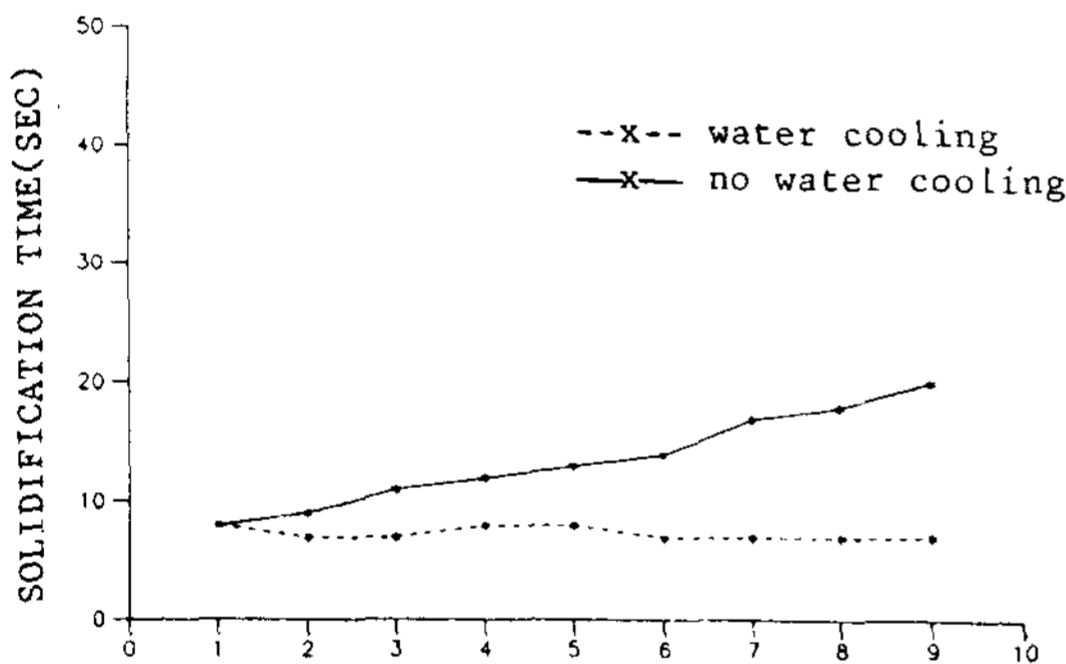

Fig. 10. Effect of water cooling on the hardness during cyclic casting.

Fig. 11. Effect of water cooling on the tensile strength during cyclic casting.

Fig. 8. Variation of eutectic solidification time with cyclic casting at the center of "T" casting.

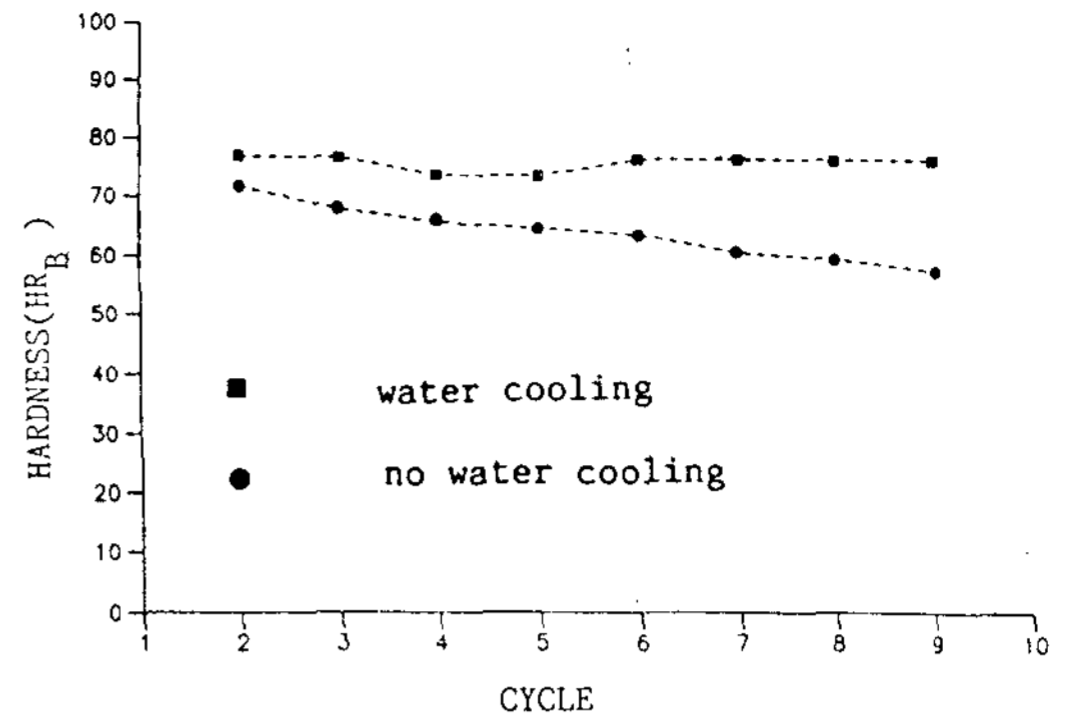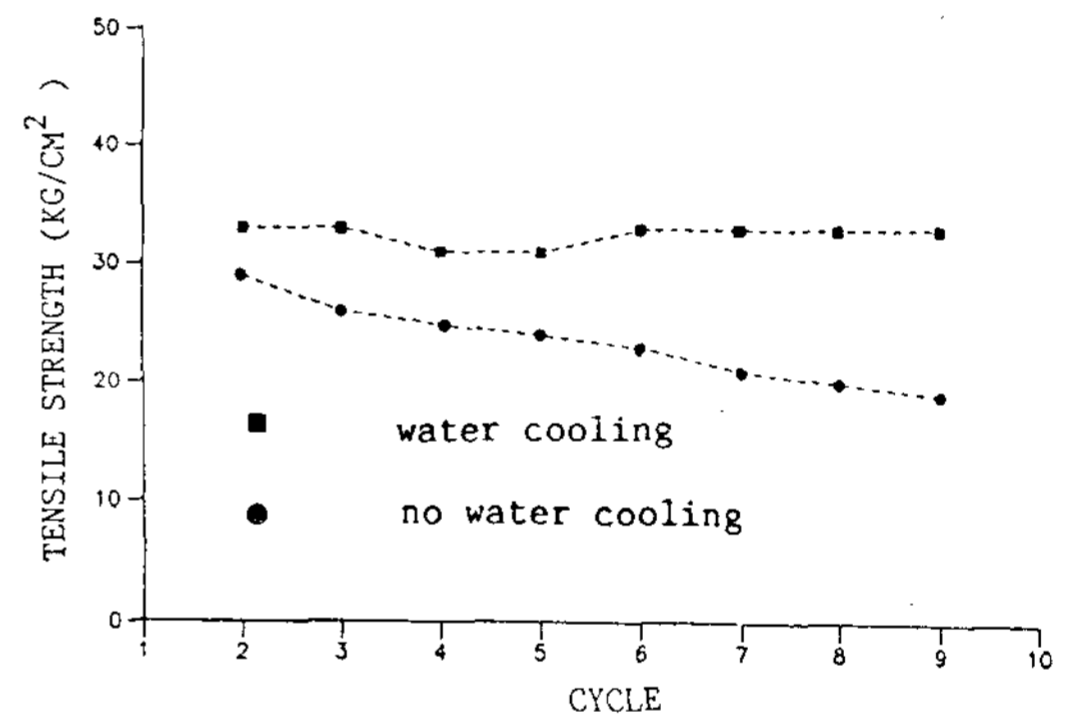**Fig. 9.** Effect of water cooling on the number of eutectic cells during cyclic casting.
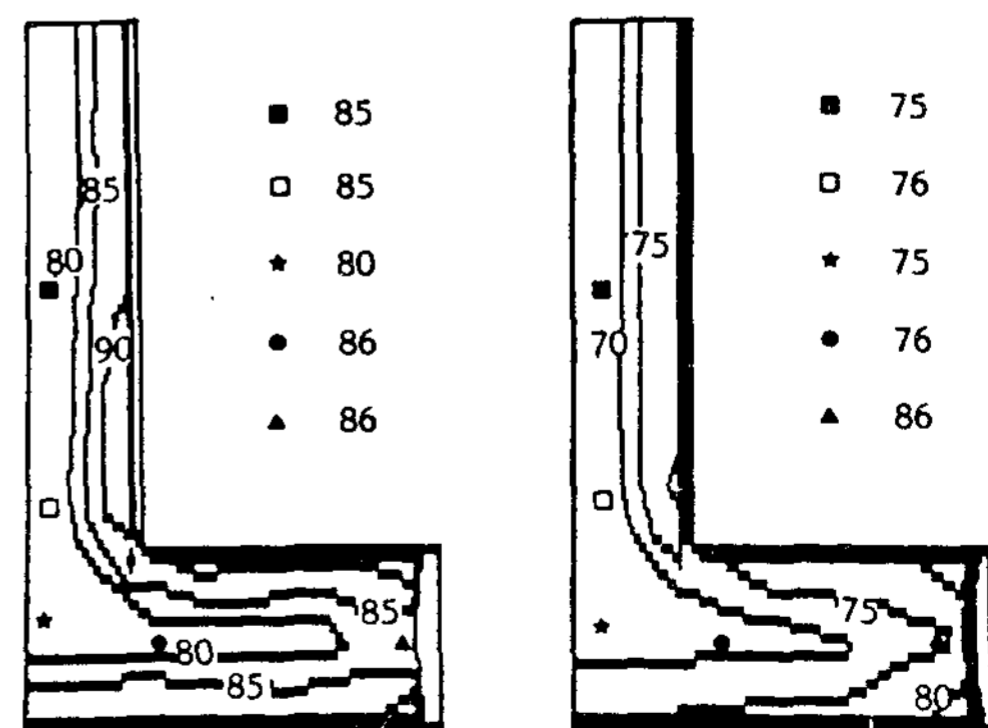

Fig. 12. Comparison of calculated hardness (HRC) distribution with experiment.

sile strength during cyclic casting is also shown in Figure 11. As shown in the figures, mechanical properties are increased with water cooling channels, and no decrease is found during cycling.

Figure 12 illustrates the comparison of calculated hardness contours and experimentally observed results in the T shape casting, (a) for with water cooling, and (b) for without water cooling channels. It shows that calculated results is relatively in good agreement with those observed in experimental castings.

5. Conclusion

In the present study, three dimensional solidification sequence has been simulated by computer during the cyclic gravity die casting of gray cast iron. The finite difference method was adopted for the main simulator.

Simulation of solidification sequence in the casting region and of thermal history in the mold region during the cyclic castings allows to predict the microstructure and mechanical properties, and to make a quantitative design of water cooling system in metal mold.

Table 1. Physical property data and initial value used to calculation

Physical Property Material	Density (g /cm3)	Specific heat (cal /g. ℃)	Heat conductivity (cal /cm · s · ℃)	Latent heat (cal /g)
Eutectic cast iron (Cast metal)	7.0	20 − 200 C : 0.128 200 − 400 C : 0.134 400 − 800 C : 0.140 800 − 900 C : 0.168 over 900 C : 0.173	20 − 200 C : 0.154 200 − 400 C : 0.124 400 − 800 C : 0.094 800 − 900 C : 0.071 over 900 C : 0.053	47
Eutectic cast iron (Metal mold)	7.0	20 − 200 C : 0.128 200 − 400 C : 0.134 400 − 800 C : 0.140 800 − 900 C : 0.168 over 900 C : 0.173	20 − 200 C : 0.154 200 − 400 C : 0.124 400 − 800 C : 0.094 800 − 900 C : 0.071 over 900 C : 0.053	−

Physical Property Material	Liquidus temp(℃)	Solidus temp(℃)	Initial temp(℃)	Surrounding temp(℃)	Heat trans. coeff. (cal /cm·s·℃)
Eutectic cast iron (Cast metal)	1158	1101	1300	−	Cast metal /Mold 0.05
Eutectic cast iron 〈Metal mold〉	−	−	−	20	Mold / Atmosphere 0.0005

Cooling channel temp.(℃) : 5

It can be concluded that proper design of water cooling channels is important for improving productivity and quality of the products, and for prolonging die life through regulating thermal history during cyclic casting.

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