論 文

Development of an Integrated Simulation System and its Application to Casting Design

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Abstract

주조방안설계를 위한 pre-processor, main-solver 그리고 post-processor로 구성된 통합 응고해석 시스템을 개발하였다. Pre-processor는 퍼스널 컴퓨터에서 사용되는 상용 CAD 프로그램인 AutoCAD를 사용하였다. Main-solver는 주조과정 중의 충진거동을 해석한 유동해석 프로그램과 3차원 열전달 응고해석을 통합하여 냉각수 시스템으로 제어되는 금형 반복주조법에서의 응고양상을 해석할 수 있다. Post-processor는 cavity내의 용탕충진거동, 주형내의 온도분포, 응고시간등을 3차원 그래픽으로 처리할 수 있게 설계하였다. 개발된 시스템의 현장적용 가능성을 검증하기 위하여 대형주강 밀하우징, 자동차휠 주조용품, 밸브블럭등의 시제품의 열유동해석에 적용하였다. 본 연구에서 개발된 *CastDesigner*는 중소기업형 주조현장에서 PC용 CAD/CAE system 구축을 통한 최적주조방안 설계용 열유동해석 프로그램으로 사료된다.

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Introduction

During the last ten years, the application of solidification simulation systems to casting design has been focused on in Korean foundries. As a result, many commercial packages, which are usually available in workstations have now been put into applications for modeling the mold filling and solidification sequences in various casting processes[1-4].

However, there are still some problems to be solved for the application of computer simulation systems in small and medium sized foundries. In most small and medium sized foundries, engineering designs and drawings are being conducted on commercial workstation based CAD systems using personal computers whether they use computer simulation systems for casting design or not. Because of financial difficulties and shortage of well trained manpower, it may nor be appropriate for small and medium sized foundries to purchase workstation based commercial packages for casting designs. Furthermore, in cases of using workstation based commercial packages, foundry engineers need to redraw complicated shapes of casting geometry for the generation of mesh diagrams which are necessary for computer simulation. They can not use their personal computer based drawings of casting geometries for computer simulation such as generation of mesh diagrams for the mold filling and solidification simulation due to the fact that most of commercial packages developed for the mold filling and solidification simulation, have their own preprocessor or commercialized ones, based on I-DEAS and CATIA etc.

It is, therefore, considered that development of a personal computer (PC) based integrated simulation system is one of the most crucial subjects for enhancing the application of the computer simulation system in small and medium sized foundries. Foundry engineers want to use their PC-based geometry data of castings for the generation of mesh diagrams, which is necessary for the further computer simulation.

In the present study, a PC-based integrated simulation system, called CastDesigner, consisting of the pre-processor, the main-solver and the post-processor, was developed for three-dimensional mold filling and solidification simulations. The pre-processor was designed available for drawing of casting geometry, solid modeling and mesh generation. The main-solver based on the finite difference method was developed for treating three subjects : 1) modeling of fluid flow during mold filling, 2) modeling of heat transfer and solidification during and after mold filling, and 3) modeling of water cooling channels in a die for the cyclic

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casting process. The post-processor was designed to depict simulation results, such as temperature distributions in the casting and die, flow patterns, mold filling sequences, and locations of shrinkage defects on a color display system. A number of simulation examples are presented to access the progress of the present system.

Descriptions of the Simulation System

Pre-processor module

In the present study, the preprocessor of Cast-Designer, which is based on the personal computer based CAD system AutoCAD R13, was used as a tool for geometric design and mesh generation of shaped castings. Using constructive solid geometry (CGS), a model of the casting may be built up from a library of primitive (Fig. 1). Complex shapes may be modelled by the union or difference of such primitives. The combinations of the shapes concerned are described by the method of Boolean algebra. An example of a casting model constructed in this way using a CGS package is shown in Fig. 2. The geometric modeler is thus used to generate two-dimensional cross-sections, which are then enmeshed in a gross manner. The mesh data generated by the modeler is then processed by a specially designed interface. Fig. 3 is the non-uniform rectangular mesh diagram. Additionally, volumes and weights can be estimated using these geometrical data.

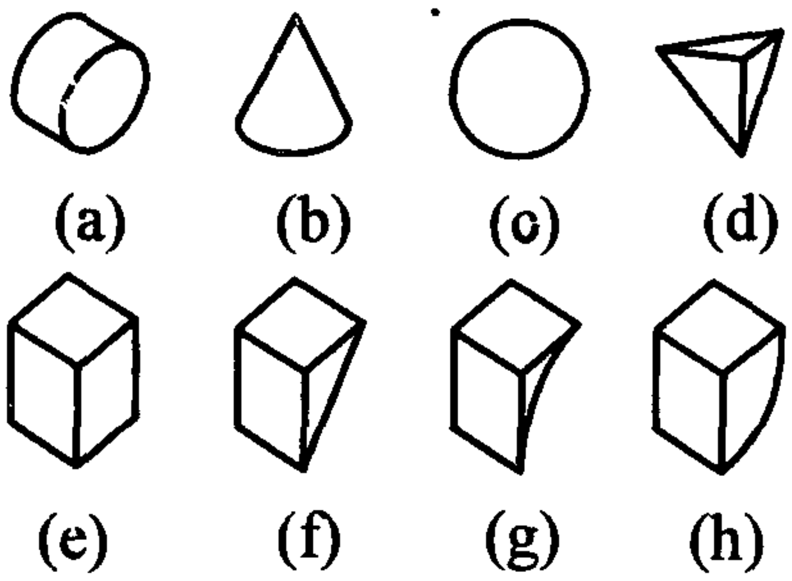


Fig. 1. Examples of typical primitives for a CGS approach.

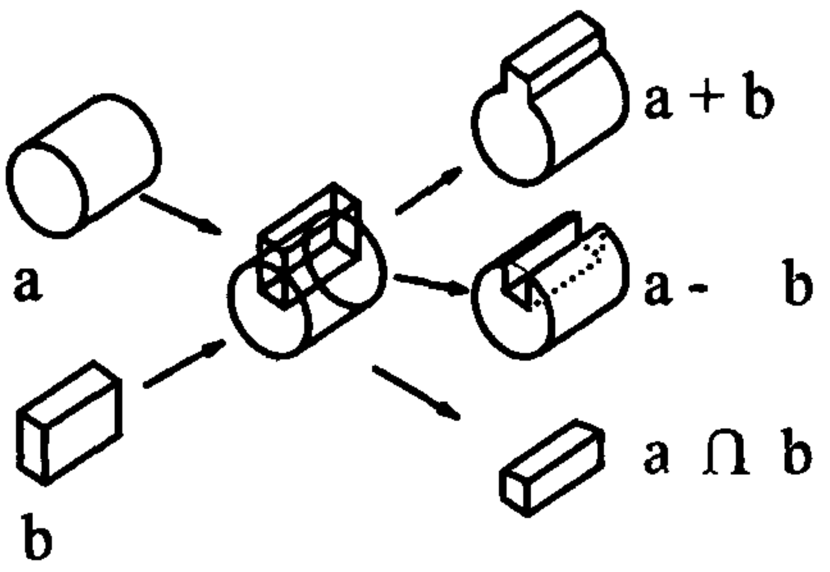


Fig. 2. A solid model constructed using a CGS package.

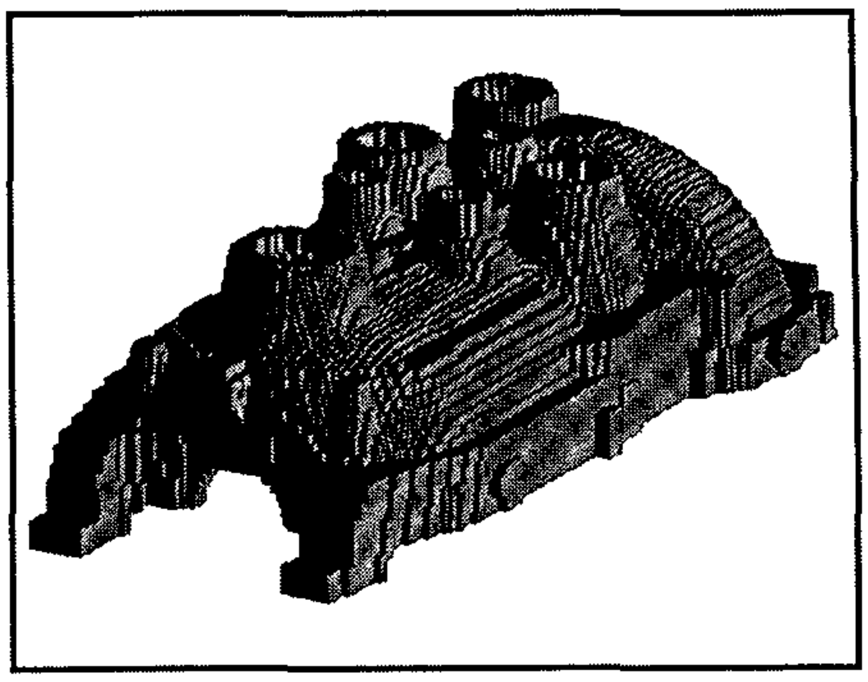


Fig. 3. An example of non-uniform rectangular mesh diagram.

Main-solver for the simulation of mold filling and solidification

The governing equations for transient fluid flow during mold filling are as follows:

Continuity equation ;

$$\nabla\cdot\vec{u}=o \tag{1}$$

Navier-Stokes equations;

$$\rho\frac{D\vec{u}}{Dt}\nabla P+\mu\nabla^2\vec{u}+\rho g=0 \tag{2}$$

where D is the substantial derivative of velocity u, P pressure, ρdensity, g gravitational constant, t time, and μ viscosity. The Navier-Stokes and continuity equations are solved by the finite difference method over regular rectangular meshes using the modified SMAC algorithm[2-3].

The governing equation for casting solidification problems is given by

$$\rho C_p\frac{DT}{Dt}=k\nabla^2T+\rho L\frac{\partial f_s}{\partial t} \tag{3}$$

where C_p indicates specific heat, T temperature, k the thermal conductivity, and L latent heat of freezing.

Three dimensional heat transfer analysis was performed by an explicit finite difference method using the same meshes used in the fluid flow analysis. In the original MAC or SMAC versions[5], marker particles are used to track the moving free surface. However, these markers can not carry any energy or mass. A new concept of energy markers which can carry energy[2] was used to calculate convective and conductive heat transfer during the filling stage.

Post-processor module

The post-processor can depict simulation results, such as temperature distributions in the casting and die, solidification time contours, temperature gradient contours, flow patterns, mold filling sequences, and locations of shrinkage defects on a color display system.

Results and Discussion

Three different types of shaped castings were simulated in order to estimate the application of the present model.

Simulation of a large steel mill housing casting

Firstly, a large mill housing steel casting in a sand mold was simulated using the present model. A schematic drawing and solid model for a mill housing is illustrated in Fig. 4. The solid model created on the AutoCAD R13 was enmeshed into 3-D non-uniform elements of 145×107×47 (total number of elements; 729,205), as shown in Fig. 5. The pre-processor can also calculate weights, surface areas, and moduli of the casting and the riser using the preprocessor, as shown in Fig. 6 and Table 1. Fig. 7 shows the calculated solidification time contours of the mill housing, which resulted in a sound casting. The computation time for solidification analysis was less than an hour using a 586 PC(RAM 128MB).

Simulation of an automobile wheel casting

Secondly, a commercial automobile wheel casting in a metal mold was chosen. The mesh diagram of this

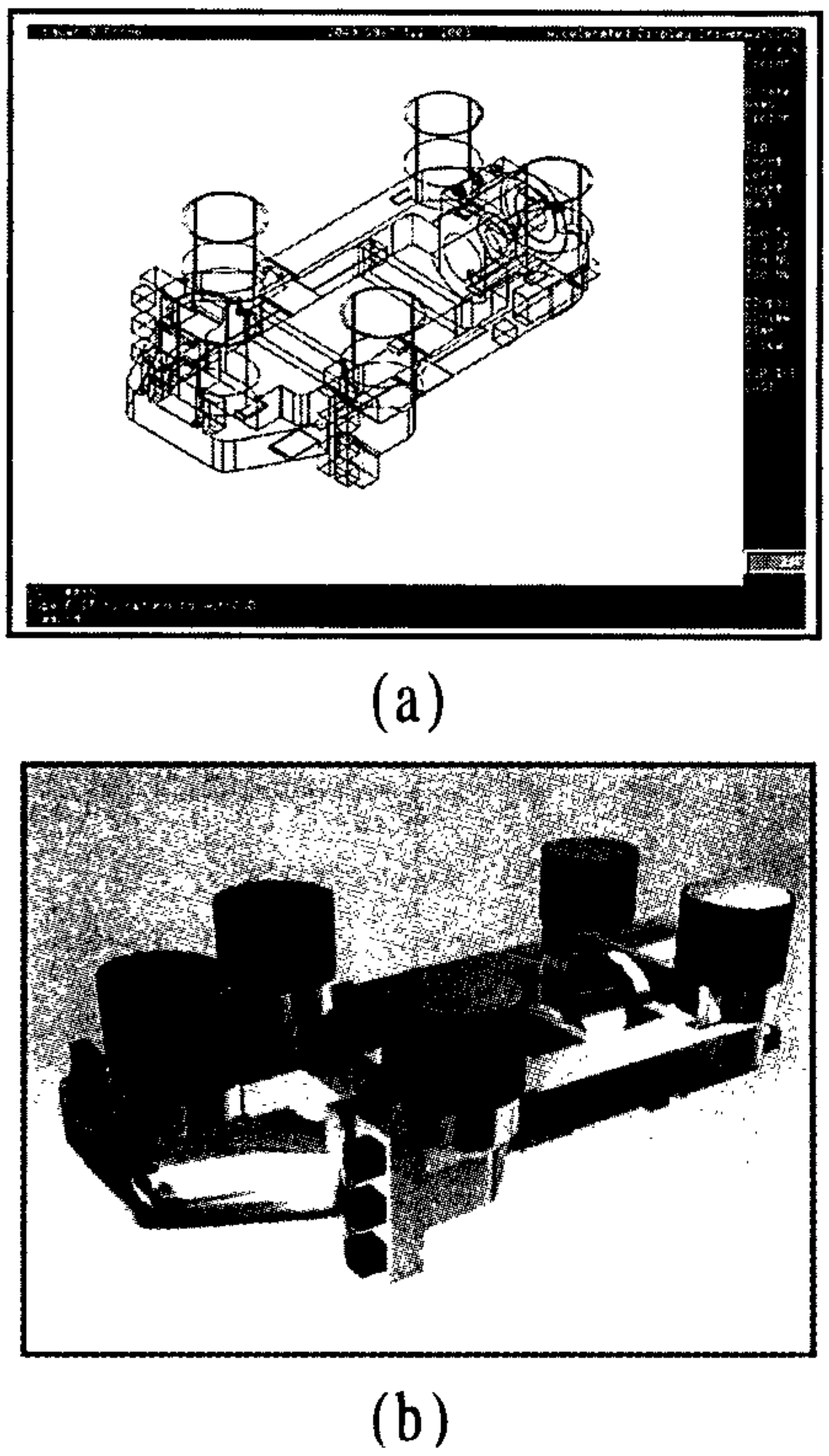


Fig. 4. A schematic drawing and solid modeling of a mill housing. (a) a schematic drawing and (b) solid modeling of a mill housing.

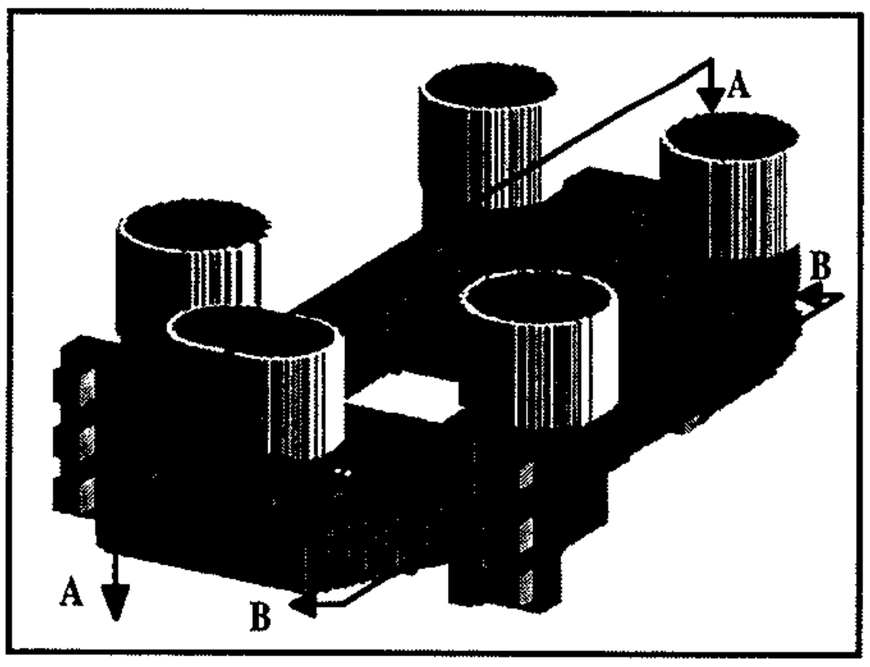


Fig. 5. A 3-dimensional mesh diagram of a mill housing.

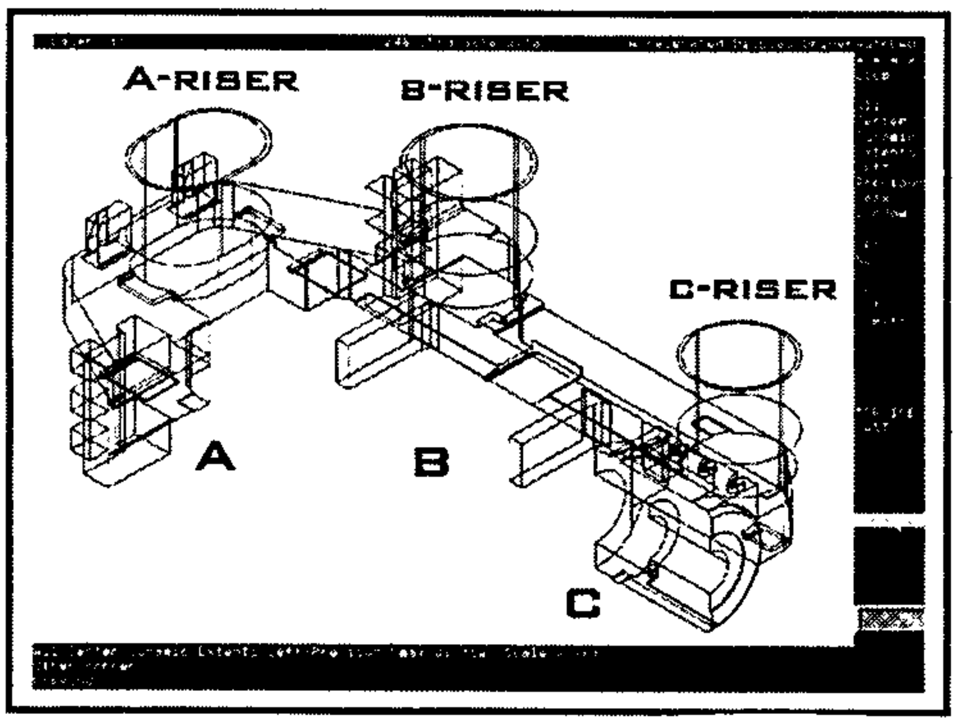
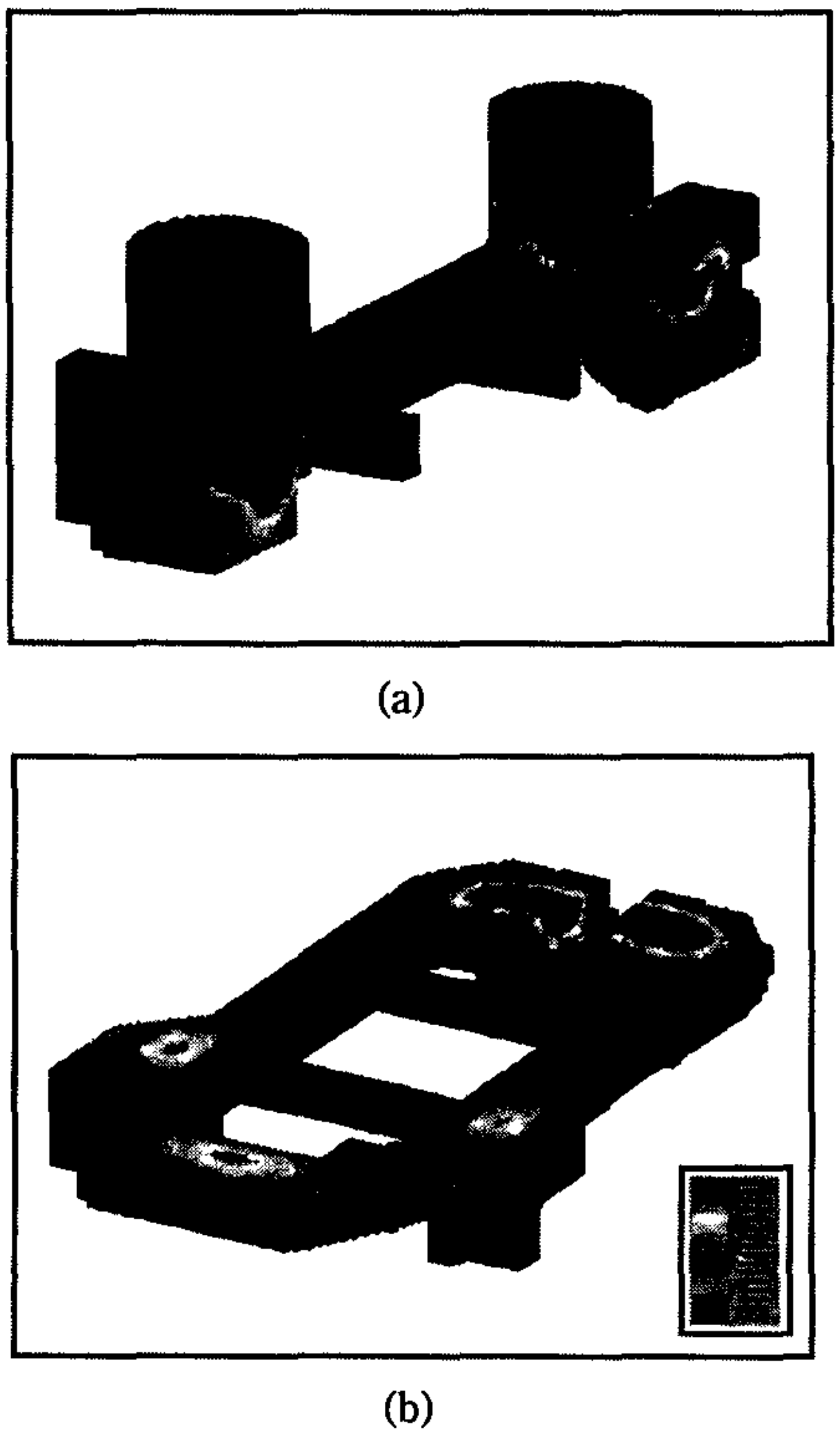


Fig. 6. A schematic drawing of a mill housing for evaluating modulus.

Table 1. Weight (W), surface area (S), and modulus (M) in the section A, B and C of a mill housing

casting			M	riser			M
A-section	W	744 kg	9.7	A-section	W	603 kg	15.0
	S	7.6 m^2			S	4.0 m^2	
B-section	W	710 kg	8.4	B-section	W	603 kg	15.0
	S	8.4 m^2			S	4.0 m^2	
C-section	W	1,565 kg	10.8	C-section	W	1,365 kg	19.6
	S	14.1 m^2			S	14.4 m^2	

casting is shown in Fig. 8. The casting region was divided into non-uniform elements of 118×64×56 (total number of elements; 422, 912). The filling sequences and temperature variation during mold filling were simulated using the present model. The calculated filling sequences and temperature distributions in the casting are shown in Fig. 9. At the time of complete filling, the maximum temperature difference between the end of the rim and hub sections was about 170°C. Temperature differences occurred inside the casting during the filling stage should be minimized in order to pre-


(a)

(b)

Fig. 7. Calculated solidification time contours of a mill housing. (a) section A-A' and (b) section B-B' in Fig 5.

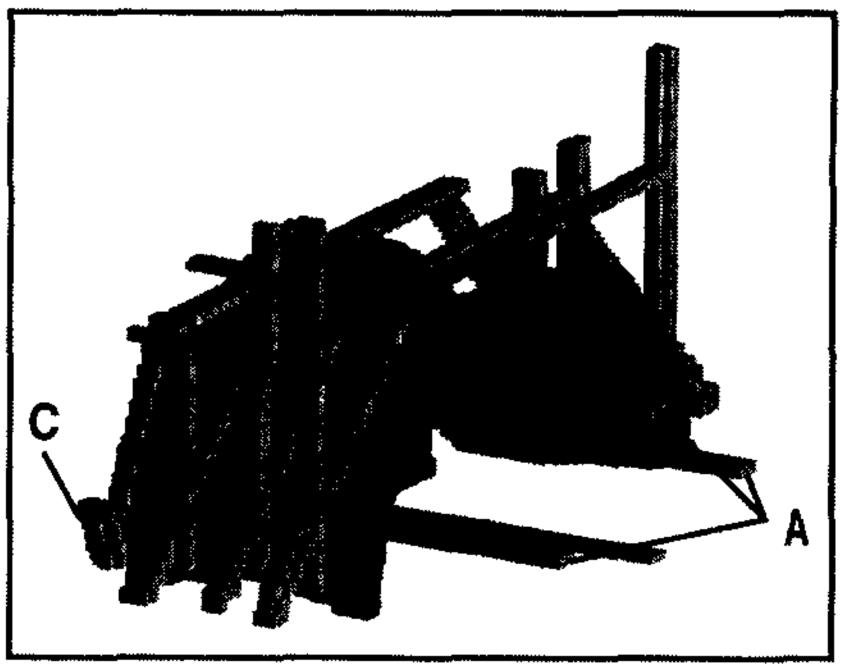


Fig. 8. A three-dimensional mesh diagram of an automotive wheel casting.

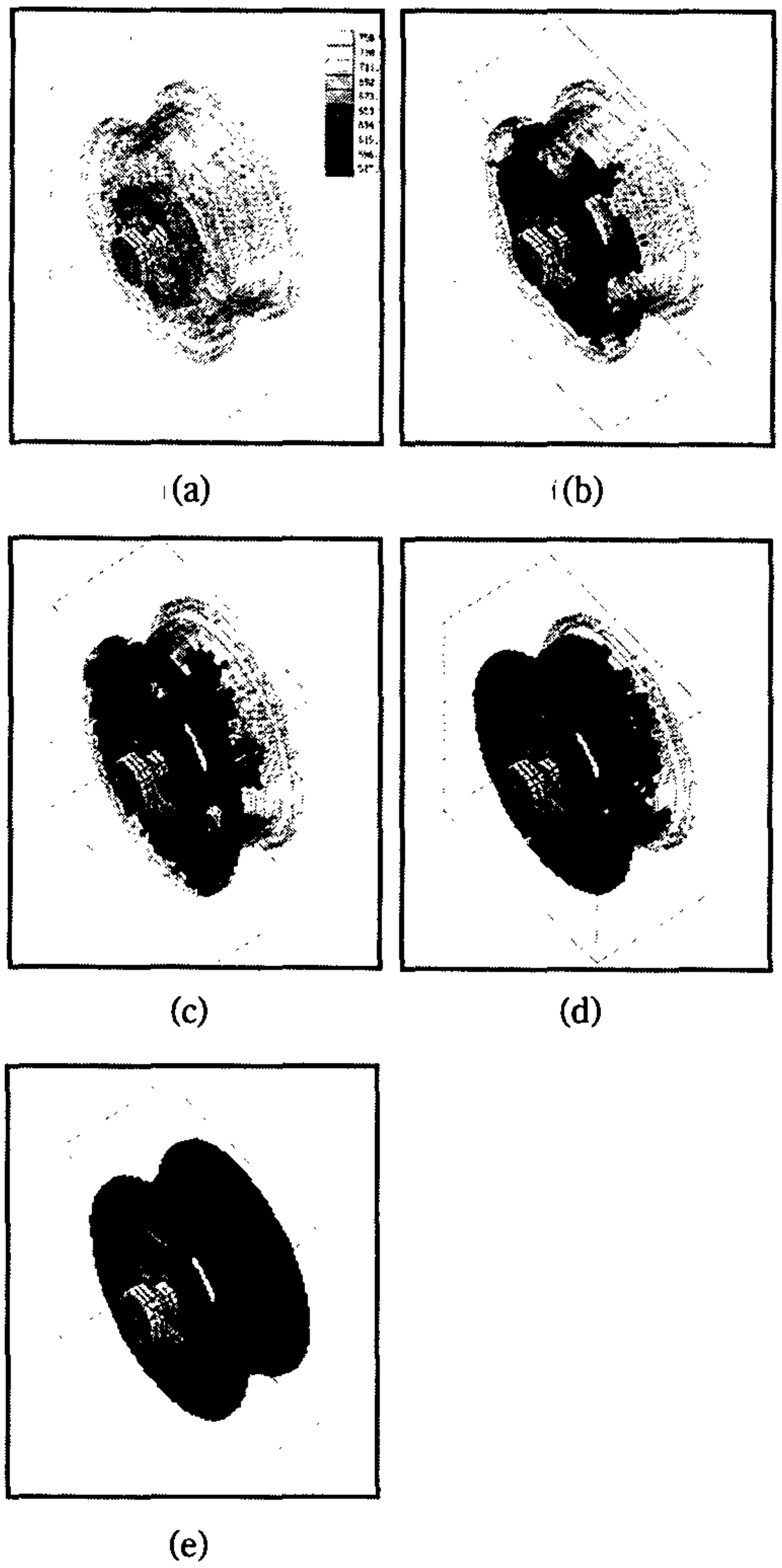
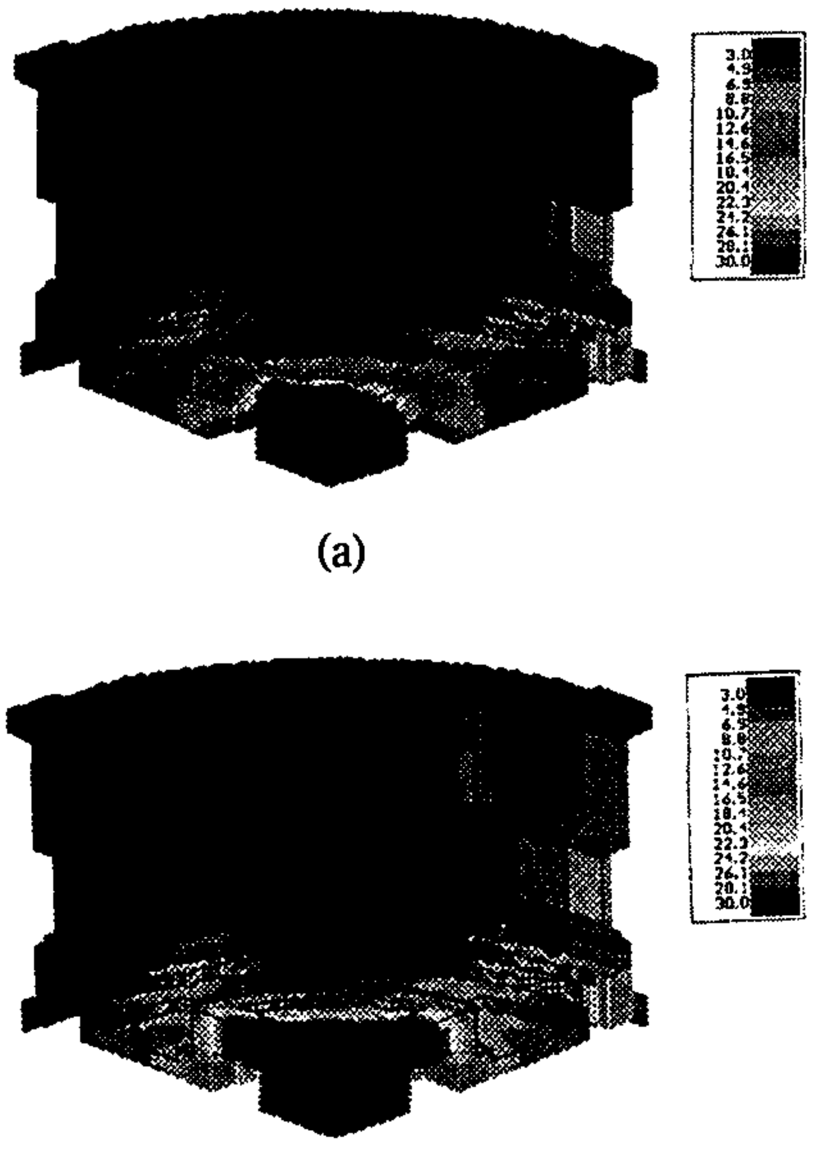

(a)
(b)
(c)
(d)
(e)

Fig. 9. Several stages of filling sequences and calculated temperature distributions of a wheel casting. (a) 20%, (b) 40%, (c) 60%, (d) 80% and (f) 100%.



(a)

(b)

Fig. 10. Calculated solidification time contours for a casting under the condition of table 2. (a) cycle 1 and (b) cycle 5

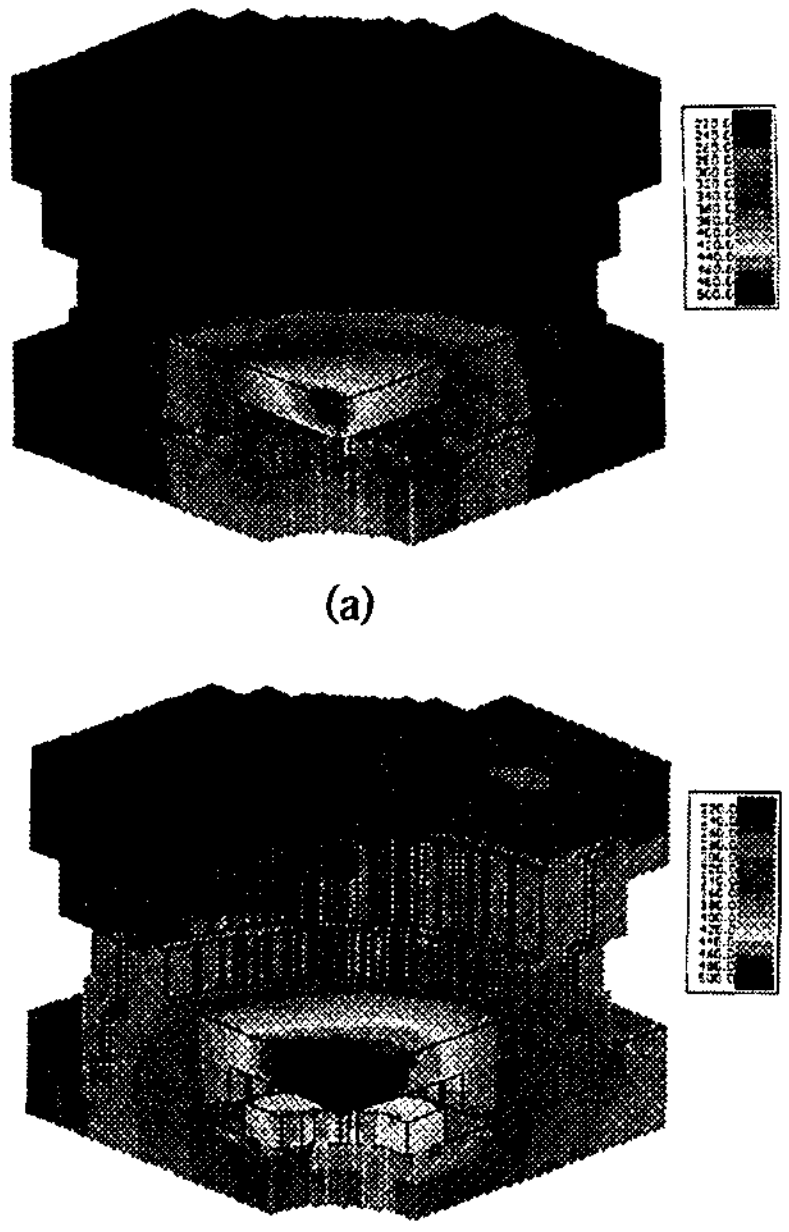
vent casting defects, such as shrinkage defects and misrun. Fig. 10 and Fig. 11 indicate the calculated solidification time contours and temperature distributions in casting cycle 1 through to casting cycle 5, when an unsuitable cooling system is used, as shown in Table 2.

Table 2. *Calculation conditions in case of an unsuitable cooling design*

Die Closing time	220 sec	Die opening time	50 sec	1 cycle time	270 sec
Cooling time	Cooling channel #A	50-100 sec after die closing: running time -50 sec			
	Cooling channel #C	*100-170 sec after die closing: running time -70 sec*			

Table 3. Calculation conditions in case of a unsuitable cooling design

7Die Closing time	220 sec	Die opening time	50 sec	1 cycle time	270 sec
Cooling time	Cooling channel #A	50-220 sec after die closing: running time -170 sec			
	Cooling channel #C	0-220 sec after die closing: running time -220 sec			

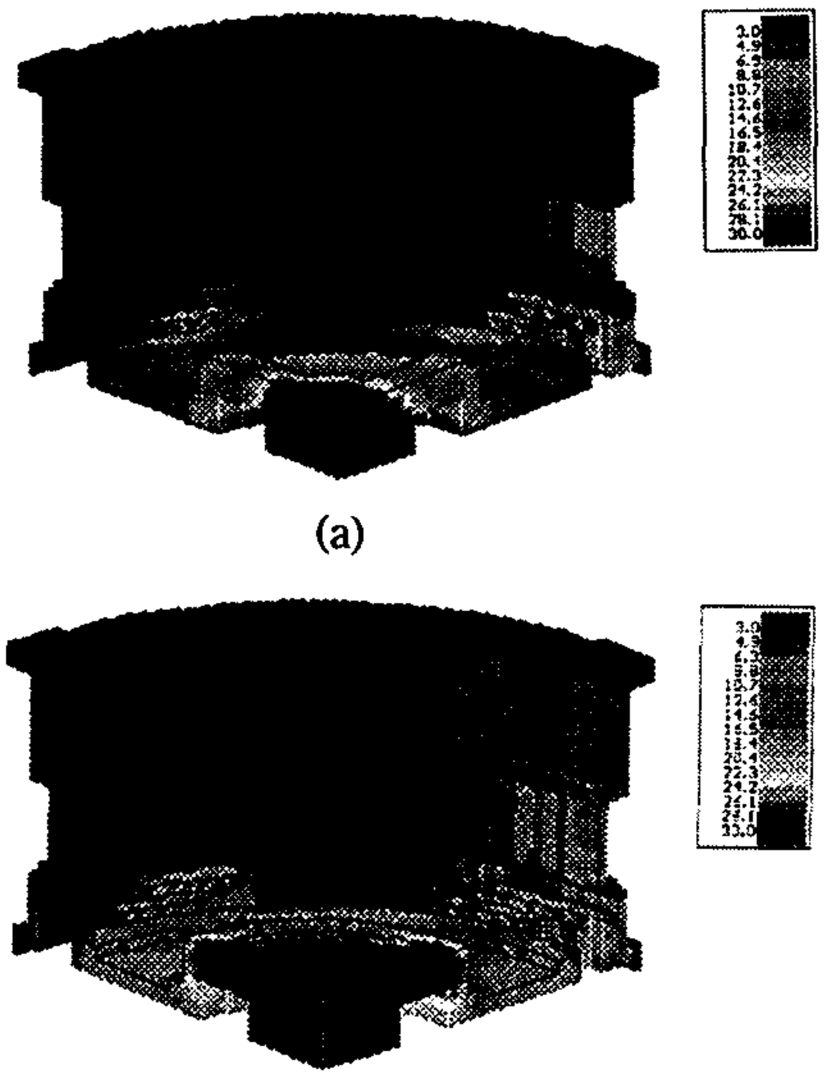


(a)

(b)

Fig. 11. Calculated temperature distributions in a die under the condition of table 2. (a) cycle 1 and (b) cycle 5

Under an unsuitable cooling condition, shrinkage defects might occur around the junction of the spoke and rim sections since solidification in this area is delayed



(a)

(b)

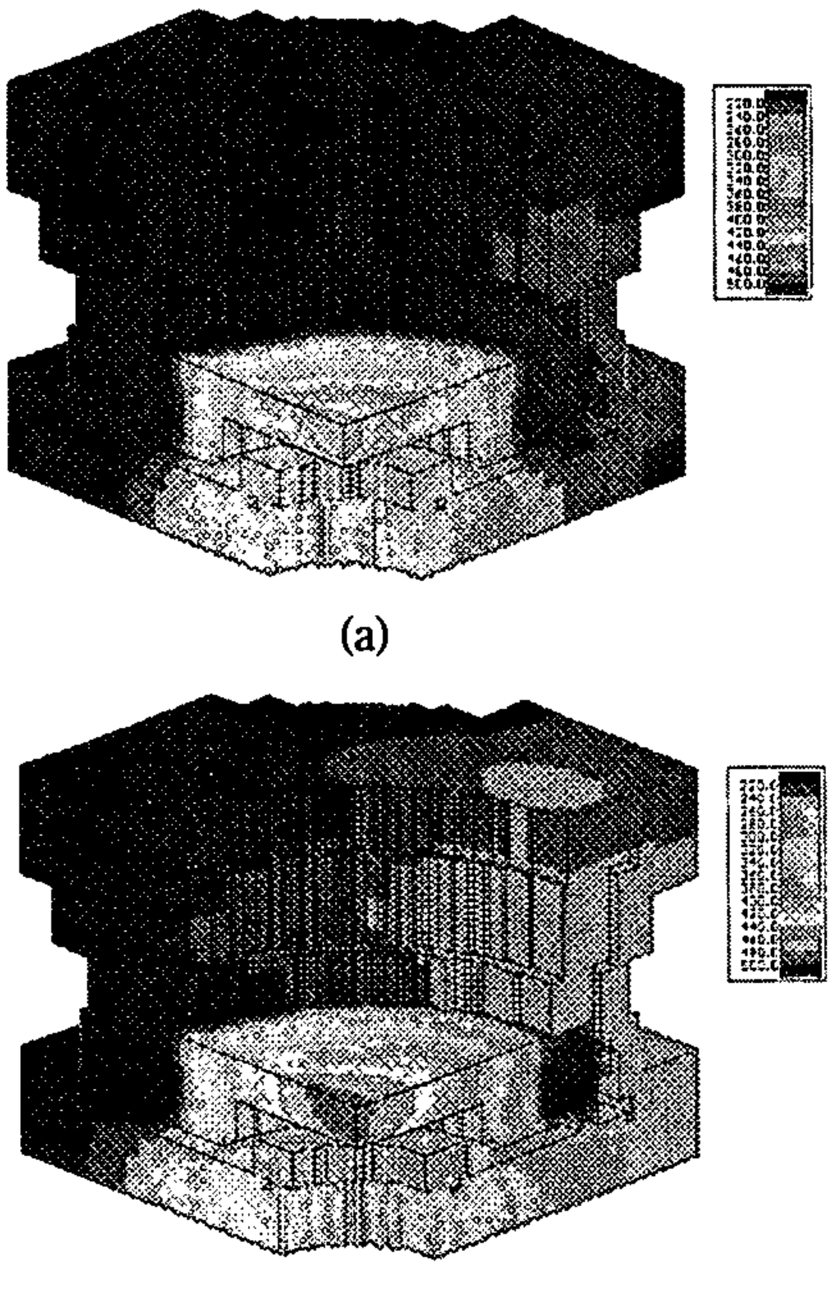
Fig. 12. Calculated solidification time contours for a casting under the condition of table 3. (a) cycle 1 and (b) cycle 5

due to the heat accumulation as the cyclic casting process repeats.

In order to solve these problems, the water cooling system was modified as detailed in Table 3. The simulated results on solidification times and temperature distributions in the die are shown in Fig. 12 and Fig. 13 for casting cycle 1 through to casting cycle 5. With a suitable water cooling system, there was no shrinkage defect observed in the experimental castings as predicted by the simulation. Fig. 14 indicates the cross sections of aluminum wheel castings produced by dies, one with improper die cooling channels, and the other with proper die cooling channels. Formation of shrinkage defects was eliminated by using a die with proper die cooling channels.

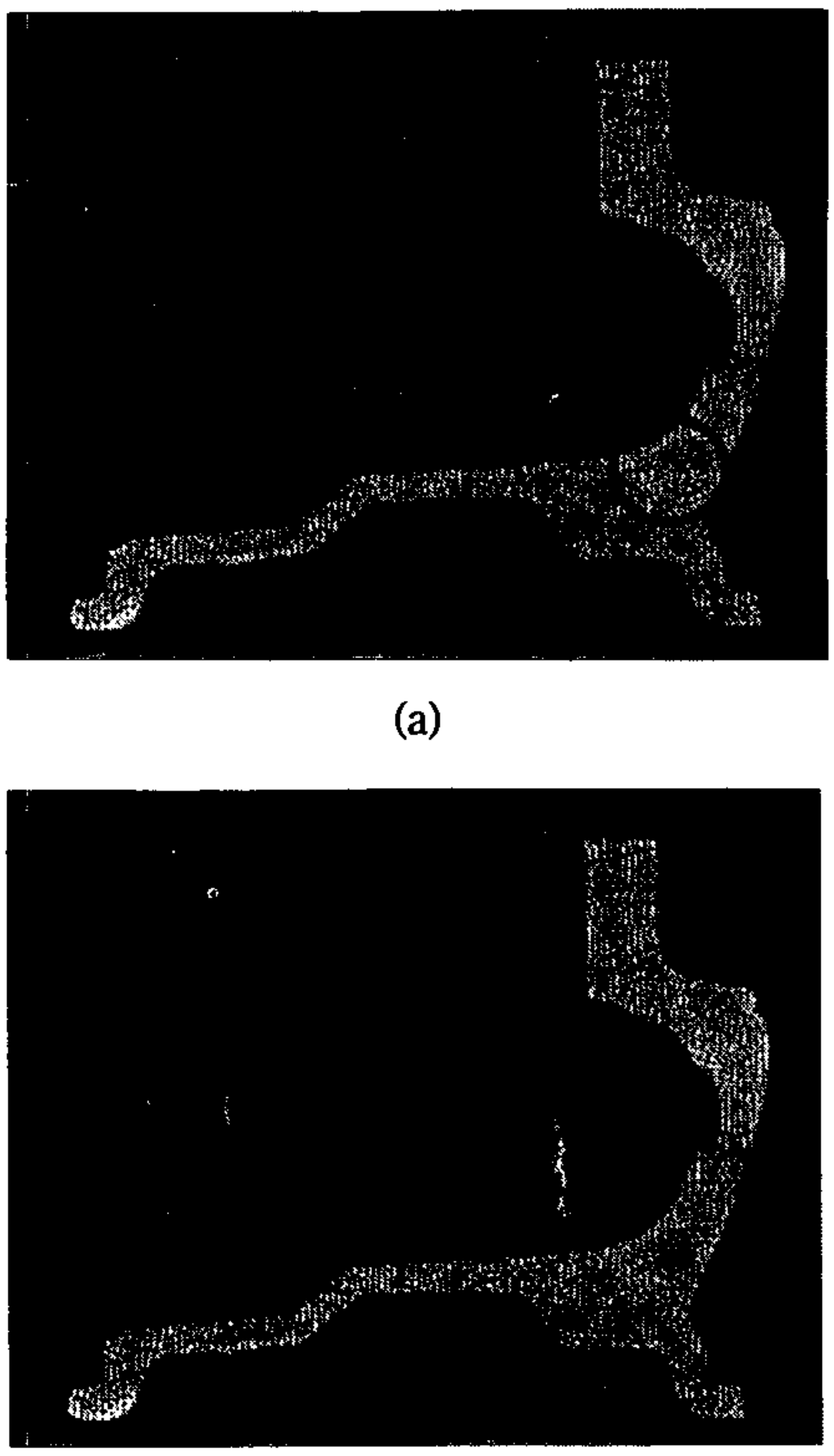
Simulation of a valve block casting

The geometry and the mesh diagram for the squeeze casting of a valve block are shown in Fig. 15 and 16. In this case, the casting region was divided into non-uniform rectangular meshes of 94×90×39 (total number of elements: 329,940). The simulated mold filling sequences and temperature variations in the central half section of the valve block casting are shown in Fig. 17. It can be seen from the figure that the molten


(a)

(b)

Fig. 13. Calculated temperature distributions in a die under the condition of table 3. (a) cycle 1 and (b) cycle 5


(a)

(b)

Fig. 14. Cross sections of aluminum wheel castings under conditions. (a) improper condition and (b) proper condition

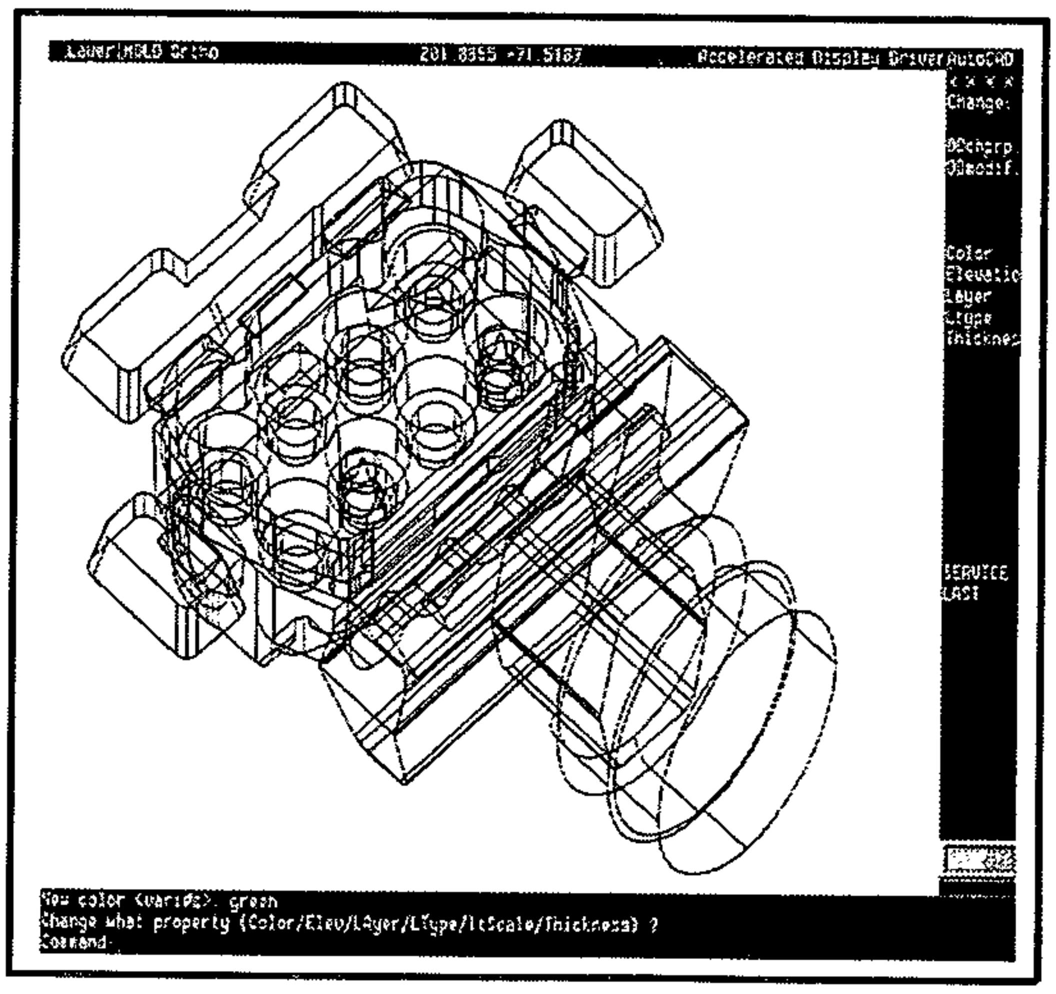


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Fig. 15. A three-dimensional drawing of a valve block.

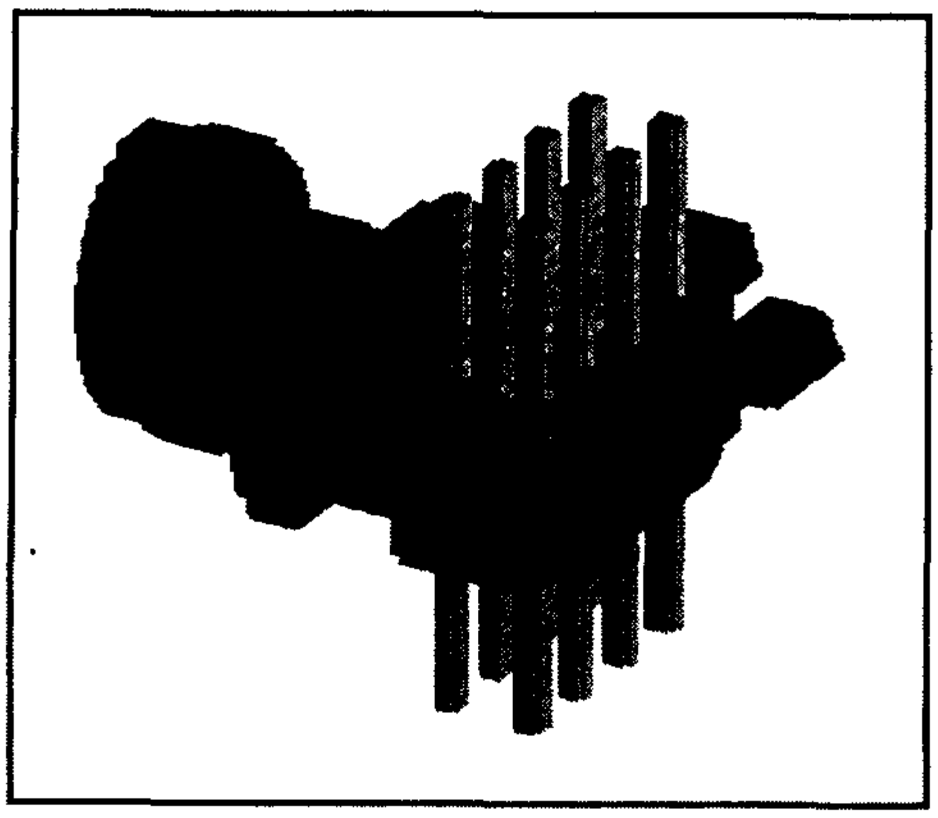
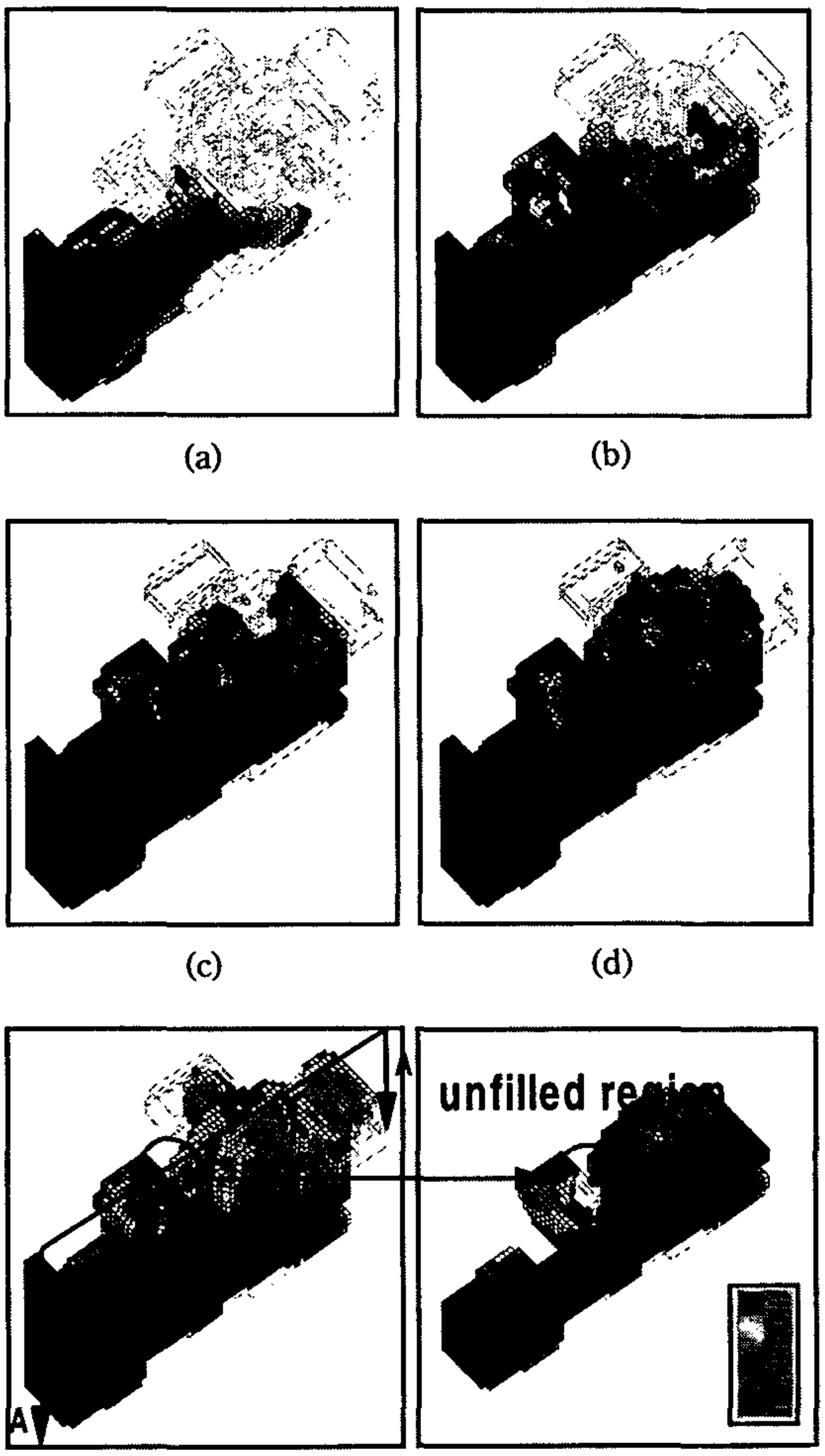


Fig. 16. A three-dimensional mesh diagram of a valve block.



(a) (b)

(c) (d)

(e) (f)

Fig. 17. Several stages of filling sequences and calculated temperature distributions of a valve block.

metal flows mostly upward near the central part of the die cavity because of relatively low resistance of fluid flow. When the stream flow fills from the central part to the upper area of the side wall, the lower area of the side wall remains incompletely filled. This means that in these areas, the upward flow meets the downward flow, which creates a vortex and results in the formation of gas blow-holes. The experimental castings showed very similar results as observed in the simulation.

Concluding Remarks

In the present study, an integrated computer simulation system, called *CastDesigner*, consisting of the pre-processor, the main-solver and the post-processor was developed for the design of castings. The pre-processor was based on AutoCAD which is available for drawing, solid modeling, mesh generation, and generation of CAM data. The main-solver can simulate the mold filling and casting solidification process, and also design the water cooling system of a die for the cyclic casting process. The post-processor can depict simulation results, such as temperature distributions in the casting and die, flow patterns, mold filling sequences, and the locations of shrinkage defects on a color display system.

A number of simulations were carried out to access the present simulation system, and the simulated results were compared with those obtained experimentally. It was found that *CastDesigner* can be successfully applied as an efficient simulation system in small and medium sized foundries.

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