論 文

Investigation of Injection Shot Parameter Effects Using Computer Flow Model in High Pressure Die Casting

Bongcheol Park†

Abstract

고압 다이캐스팅에서 요구되고 있는 고품질의 주조를 위해, 비교적 간단한 개선 방안으로 용탕 주입 방법의 개선이 실험적으로 시도 되었으며, 그로 인해 많은 경우에 긍정적인 결과가 관찰 되었다. 특히, 냉가압 다이캐스트에서, 금형내 용탕의 예충전을 유도하는 용탕 주입의 속도 및 플렌저의 위치제어를 통해 기공율의 저하 및 그로 인한 기계적 강도의 개선 효과를 확인 할 수 있었다. 본 논문은, 그 원인과 결과에 대한 연구를 위해, 상용 해석 도구인 Flow3D를 이용, 금형내 용탕의 흐름을 모델링을 통해 가시화하여 용탕의 주입속도 및 위치의 변화가 주물의 품질에 미치는 영향을 조사하였다. 용탕 주입을 위한 플런저의 속도 및 위치 제어의 변수로, 1) 금형내에 용탕의 예충전 유도를 위한 용탕 고속 주입 지연 정도, 2) 플런저의 저속운행에서 고속으로의 가속도, 3) 용탕의 예충전 동안의 플런저 속도를 선택, 그로 인한 영향을 연구 분석 하였고, 그 결과로 플런저의 속도 및 위치 조절을 통하여 금형내 갇힌 공기의 양이 줄어 들 수 있음을 알 수 있었다.

Key words : Die Casting, Injection Shot Parameters, Air Entrapment, Cavity Pre-fill, Porosity.

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1. Introduction

Die casting process is a high volume production rate process, which produces various nonferrous castings including aluminum, zinc and magnesium alloys with superior surface finishes. However, as die castings are produced by forcing molten alloy under pressure into metal molds and solidifying it in the die, porosity is one of the biggest problems causing unwanted casting defects. The porosity causes leaks and reduces surface quality and the average mechanical properties of castings. Recently, the demand for high quality die casting has increased especially in the field such as an automobile part which needs a heat treatment to obtain a high strength.

Shrinkage and gas are two major causes of porosity and they are often called gas porosity and shrinkage porosity. The shrinkage porosity is associated with the hottest local point in the casting, or the last point to solidify in any given area. The gas porosity has four sources: 1) trapped air that is entrained in the injection system and cavity; 2) gas generated from burned lubricants; 3) gas generated from water that may be in the cavity and 4) hydrogen gas[1]. The gas porosity due to trapped air is an unwanted byproduct of the relatively high velocity injection method used. Gas entrapment is caused by turbulent flow pattern generated during metal injection process and the location, size and total volume of contained gas porosity are influenced by the method chosen to fill the cavity with molten alloy.

Some efforts have been made to reduce air entrapment by the modification of conventional injection shot profile taking advantages of the development of advanced and reliable shot control systems built in die casting machines. The assessment of critical slow shot to minimize air entrapment in the shot sleeve[2,3] and the investigation of the effects of dual injection speed in cavity filling on air entrapment in the die cavity[4] are the examples. Similarly, in industry, some various degrees of cavity pre-fill, which means that the casting cavity is partially

Graduate School of Automotive Engineering, Kookmin University, Seoul 136-702, Korea
†E-mail : bcpark@kookmin.ac.kr

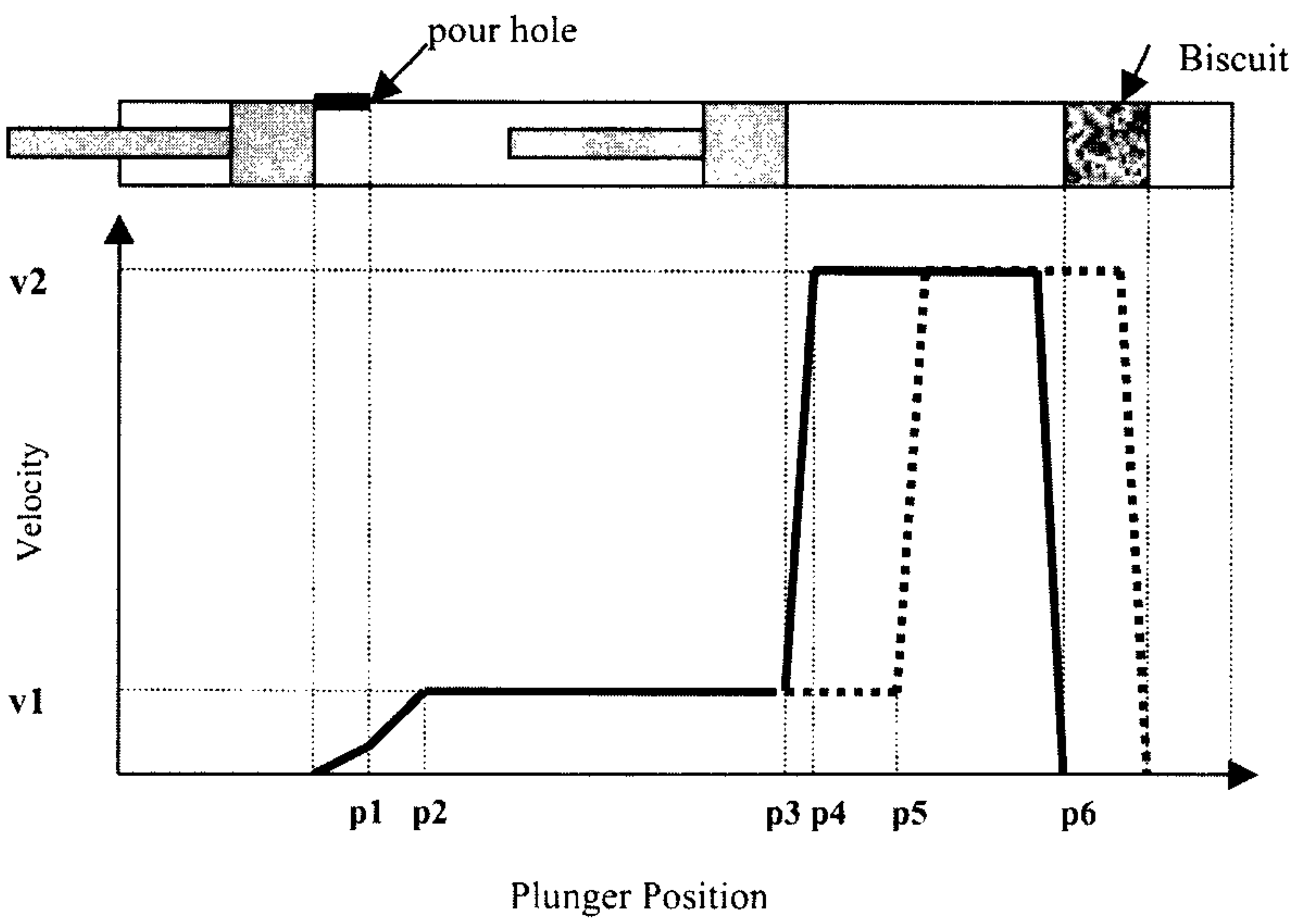
filled with molten alloy using slow shot velocity before fast shot starts (Fig. 1), have been applied in cold chamber die casting. These practices have shown equal or superior quality of castings in terms of porosity and mechanical strength associated with it, as compared to castings made by conventional approach that fast shot starts immediately after shot sleeve and runner system are full of molten metal by slow shot.

Unfortunately, however, injection shot parameters for machine set points, such as pre-fill percentage and plunger acceleration rate from slow to fast shot for the maximum quality castings in terms of air entrapment are not well assessed. Most injection shot parameters used in industry are determined by trial and error method. When the effects of injection parameters associated with cavity pre-fill and plunger acceleration rate for maximum quality casting in terms of air entrapment are investigated and addressed, expected benefits of the results to the die casting industry are to reduce the machine parameter "tryout" time for quality castings. In addition, the research has the potential for aiding design engineers in designing gates and vents associated with selected cavity filling method a concurrent engineering approach for the maximum performance.

2. Computer Flow Model

Fluid flow of molten alloy during the filling stage of the die cavity is highly transient, inertia dominated and often turbulent with Reynolds numbers in excess of 10,000 due to high velocity of molten metal and rapidly changing its flow path in the casting cavity. Within the die cavity, jetting, splashing and liquid droplet and atomized spray formation are quite common[5].

Unlike modeling the flow of sand casting and injection molding, for fluid flow model in die casting, the solution of the complete Navier-Stokes equations including the convection terms to calculate transient velocity and pressure changes is an essential requirement. The other requirement is free surface modeling of the fluid flow,



p1-p2; Transition to critical slow shot velocity
p2-p3; Constant critical slow shot
p3; Where shot sleeve & runner systems are full of metal
p3-p4; Transition from slow to fast shot
p3-p5; Cavity pre-fill duration in pre-fill approach
p6; Where Cavity fill completed, intensification pressure engaged
v1; Critical slow shot velocity
v2; Fast shot for cavity fill

Fig. 1. Shot profile (Conventional vs. Pre-fill approach)

which is capable of tracking complicated flow fronts as well as the formation of jets and flow separation caused by high velocities. In addition, the model should adequately handle the three dimensional geometry of die cavity that is often very complex in die casting[6].

Flow-3D® software package has been used for this study since above requirements for flow model are satisfied and its superior free surface modeling capability, which allows the handling of complicated free surface movement is very important for this research purpose to investigate metal filling patterns in the cavity. The software is a three dimensional finite difference CFD code, which is an extension of SOLA and SOLA-VOF family of free surface modelers[7]. In spite of FDM code, using FAVOR (Fractional Area Volume Obstacle Representation) algorithm, Flow-3D® has a capability to represent complex geometry nicely while preserving the simplicity of numerical scheme.

3. Modeling

The model is to visualize filling patterns in the die cavity and evaluate relative performances in terms of air entrapment with respect to the use of different parameters in cavity pre-fill injection method. It is assumed that; 1) pre-occupied air in the die cavity is under the pressure of atmosphere (e.g. 1,013,250 dyne/cm^2), 2) vents are the only way for the air to escape from the cavity, 3) molten metal flow is viscous and incompressible fluid flow, 4) air inside the cavity acts as perfect gas, so that equation PV^{γ}= constant is applicable for modeling of the back-pressure effect, 5) the properties of fluid (molten Aluminum) are based on Smithells Metals References 6th edition,1983 (e.g. at T=660°C, density=2.38 g/cm^3, surface tension=914 dyne/cm, dynamic viscosity=0.013 g/cm sec), 6) metal flow is in isothermal condition in such a short fill time and even at die contact.

Critical slow shot velocity[4,5] to minimize air entrapment in the shot sleeve is used for slow shot cavity pre-fill velocity primarily. The critical slow shot velocity of plunger (Fig. 1) is calculated to be 31.88 cm/sec based on gate area 0.94 cm^2, shot sleeve inner diameter (5.08 cm (=2 inches)), shot sleeve length (60.96 cm (=24 inches)), initial fill percentage of shot sleeve (60%), and acceleration (4.45 cm/sec^2) to reach critical slow shot velocity. Fast shot velocity (e.g. gate velocity = 3870 cm/s) is employed based on NADCA (North American Die Casting Association) recommendations as a fixed shot parameter.

Based on the above assumptions and fixed process parameters, the effects of two parameters (e.g. percentage of cavity pre-fill and transition time from slow to fast shot), which are considered to be important in cavity pre-fill shot injection, are investigated. The experiment range of two parameters are established based on practical uses in industry, such as 0, 10, 20, 30, 40% of cavity volume pre-fill and 10, 20, 30 milliseconds of transition time from slow to fast shot. While critical slow shot velocity (e.g. 31.88 cm/sec of plunger velocity) is employed primarily as a slow shot cavity pre-fill velocity, 70% of critical slow shot velocity is also tested as a pre-fill velocity to investigate the effects of cavity pre-fill velocity in terms of air entrapment and fill patterns (Fig. 3).

The quantitative analysis of air entrapment in the cavity is possible under the second assumption above. The air inside the cavity should be trapped in the die cavity and the pressure of the air should increase as molten metal is injected in the cavity as soon as all the vents are closed with molten metal flow. Thus, the air entrapment in the die cavity is estimated by measuring unfilled cavity volume (% of cavity volume).

3.1. Cavity geometry

To investigate the effects of cavity geometry on filling patterns, two different geometries of rectangular cavity are employed for the model. One is simple rectangular

Table 1. Properties of Molten Aluminum Used for Modeling.

Density of Molten Aluminum	2.38 g/cm^3 at T=660°C
Surface tension of Molten Aluminum	914 dyne/cm at T=660°C
Dynamic viscosity of Molten Aluminum	0.013 g/cm·sec at T=660°C

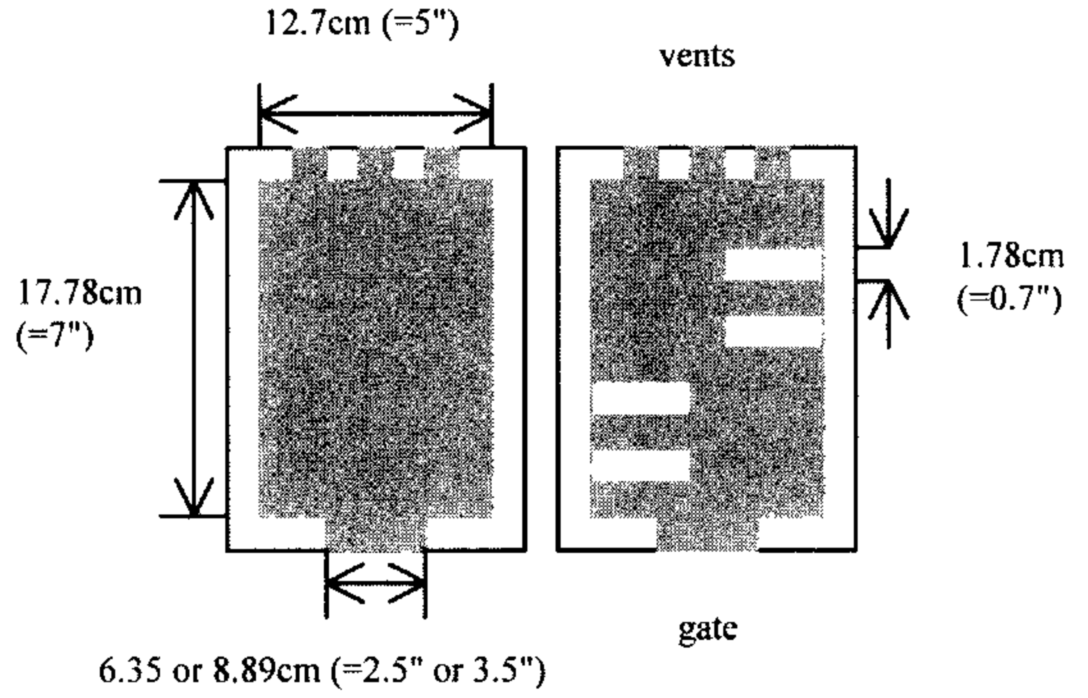


Fig. 2. Cavity geometry - Simple and Cavity with ribs.

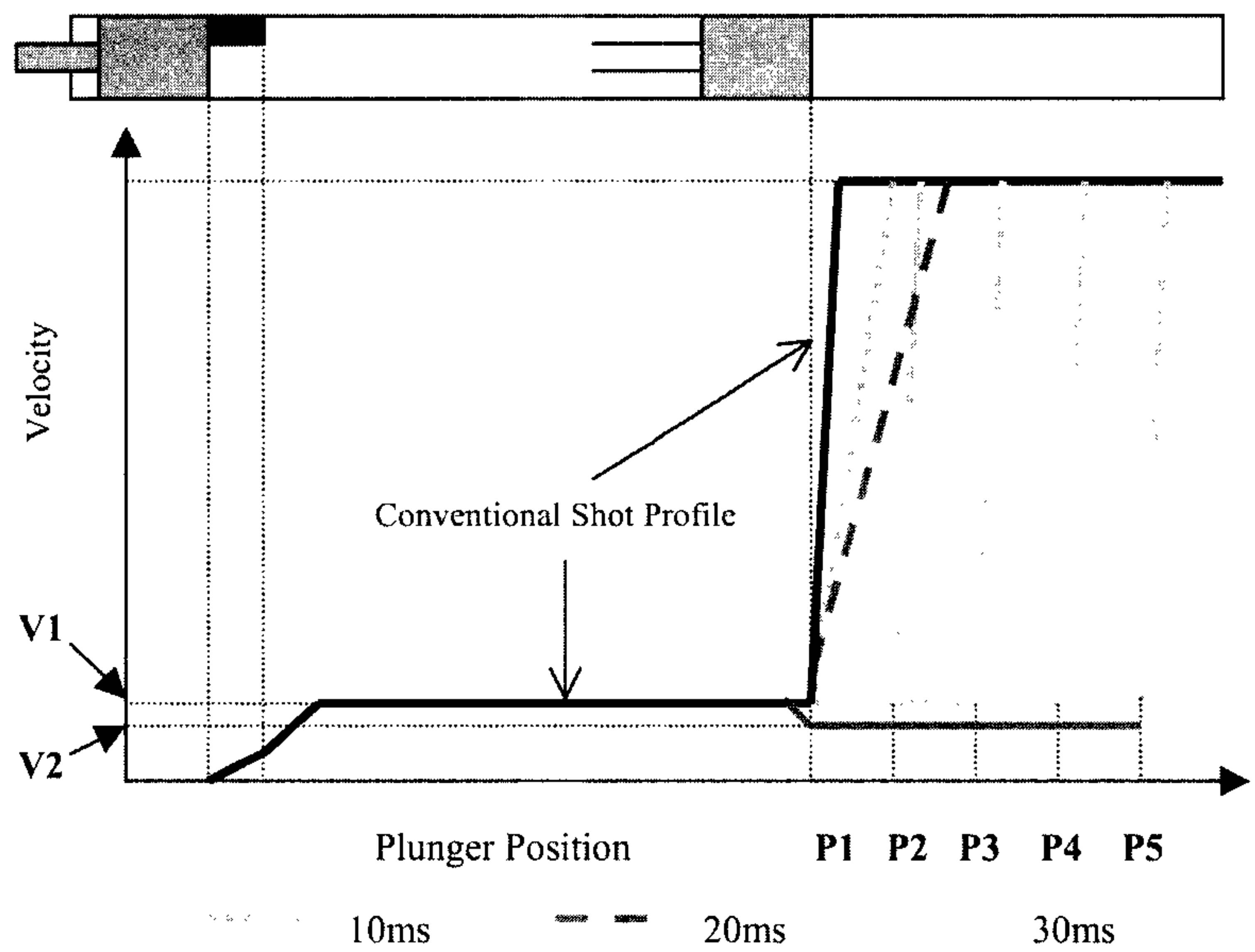
plate cavity (12.7 cm × 17.78 cm (=5" × 7")) with chisel gate and another has four ribs (1.78 cm × 6.35 cm (=0.7" × 2.5")) - two ribs are on the left wall at the bottom and the other two are on the right side of wall at the top-inside the cavity (12.7 cm × 17.78 cm) with chisel gate, which generates more turbulence of flow in the cavity (Fig. 2).

In addition, two different widths of gates (wide; 8.89 cm(=3.5") & narrow; 6.35 cm(=2.5"), which are 70% and 50% of cavity width) are also employed to investigate the effects of gate width on air entrapment and flow patterns in the die cavity.

4. Results and discussions

4.1. Effects of pre-fill percentage.

Fig. 4 shows the sequence of cavity filling in the simple cavity geometry with narrow gate width (6.35 cm) when transition time of 10 ms is employed. It was clearly shown that fill pattern is influenced by cavity pre-fill in some degrees. Especially, more lateral expansion of flow in cavity was observed when cavity pre-fill was used, which is desirable in terms of air entrapment since flow is injected more before vents are sealed(blocked) with molten metal. However, using too much pre-fill percentage (e.g. 40%) delays fast shot engagement, so that lateral expansion of flow was relatively weak before the vents are sealed. In this particular geometry and transition



P1; 0% no pre-fill, plunger position when shot sleeve is filled
P2; 10% pre-fill, plunger position when 10% of cavity is filled
P3; 20% pre-fill, plunger position when 20% of cavity is filled
P4; 30% pre-fill, plunger position when 30% of cavity is filled
P5; 40% pre-fill, plunger position when 40% of cavity is filled
V1; Critical slow shot velocity
V2; 70% of critical slow shot velocity during cavity pre-fill

Fig. 3. Shot Profile Modification on Cavity Pre-fill

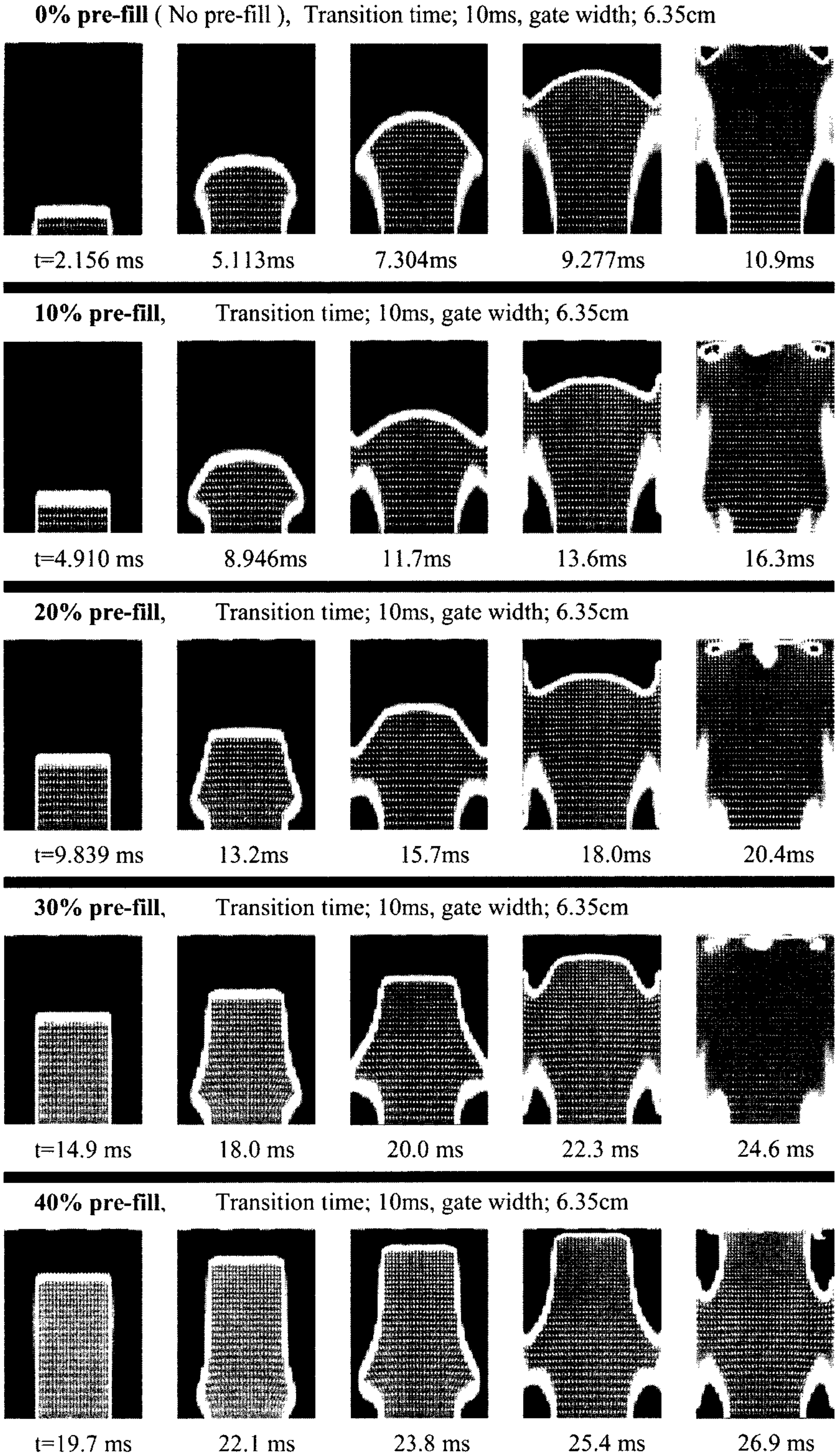


Fig. 4. The effects of cavity pre-fill on filling pattern in simple die cavity

time(10 ms), 10, 20, 30% of cavity pre-fill generate much better filling pattern in terms of air entrapment compared to the injection without using cavity pre-fill. Especially, using 30% of cavity pre-fill produced the least air entrapment generating larger lateral expansion of flow (Fig. 4). Unlike using narrow gate(6.35 cm), for simple cavity with wide gate(8.89 cm), cavity pre-fill effects on the amount of air entrapment are not shown much (Fig. 7-1, 7-2).

On the other hand, in the die cavity with ribs inside with wide gate(8.89 cm) and 10 ms of transition time (Fig. 5), it was observed that the more pre-fill percentage

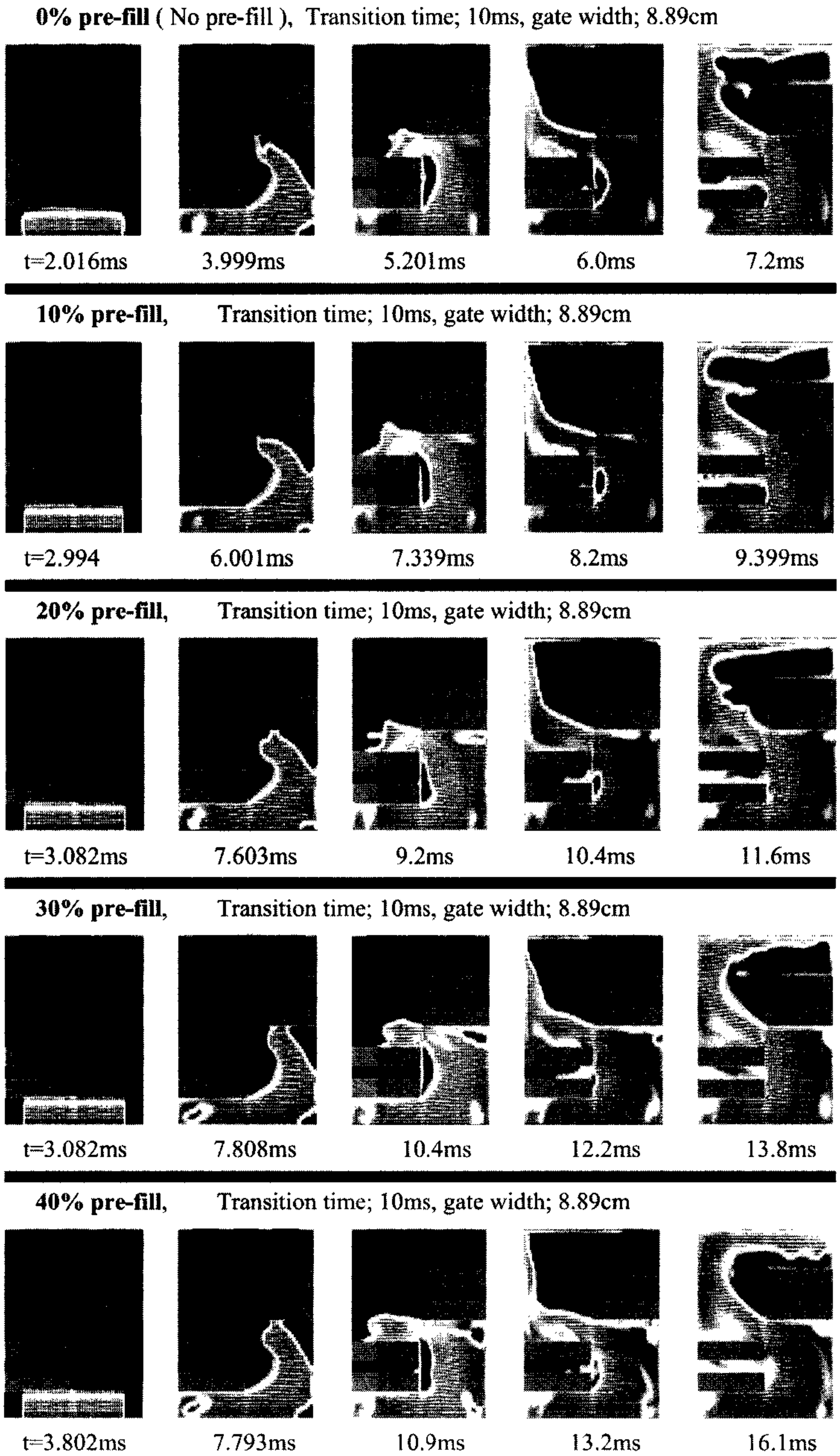


Fig. 5. The effects of cavity pre-fill on filling pattern in the cavity with ribs

is used, the better fill patterns in terms of air entrapment are achieved. Relatively low inertia of flow during pre-fill and lateral expansion of flow due to fast shot engagement right after pre-fill generates relatively uniform cavity fill. Especially, in predictable defect area (air pocket), the gap between bottom two ribs was found to be improved in terms of filling due to lateral expansion of the flow when cavity pre-fill was used. Like simple geometry cavity fill, pre-fill effects on air entrapment in cavity were larger with narrow gate than with wide gate.

4.2. Effects of Transition Time from Slow to Fast Shot

In addition to pre-fill percentage, the transition time from slow to fast shot on cavity filling patterns was found to be one of important parameters in cavity filling patterns. When cavity pre-fill was not employed, the flow front of jet stream was observed to be changed as transition time changed. The longer transition time was used, the wider flow front was developed. With cavity pre-fill, transition time from slow to fast shot decide how fast lateral expansion of flow would be. Since the pre-filled flow is pushed up by incoming second fast shot without changes of very flow front, long transition time with high pre-fill percentage can generate unwanted filling patterns in terms of air entrapment (Fig. 6). Therefore, appropriate combination of transition time and pre-fill percentage should be used to achieve best performance to minimize air entrapment. For example, in Fig. 7-2, while 10 ms & 30% pre-fill shows best performance in terms of air entrapment, 20% pre-fill was the best when 20 and 30 ms of transition time was employed. Overall,

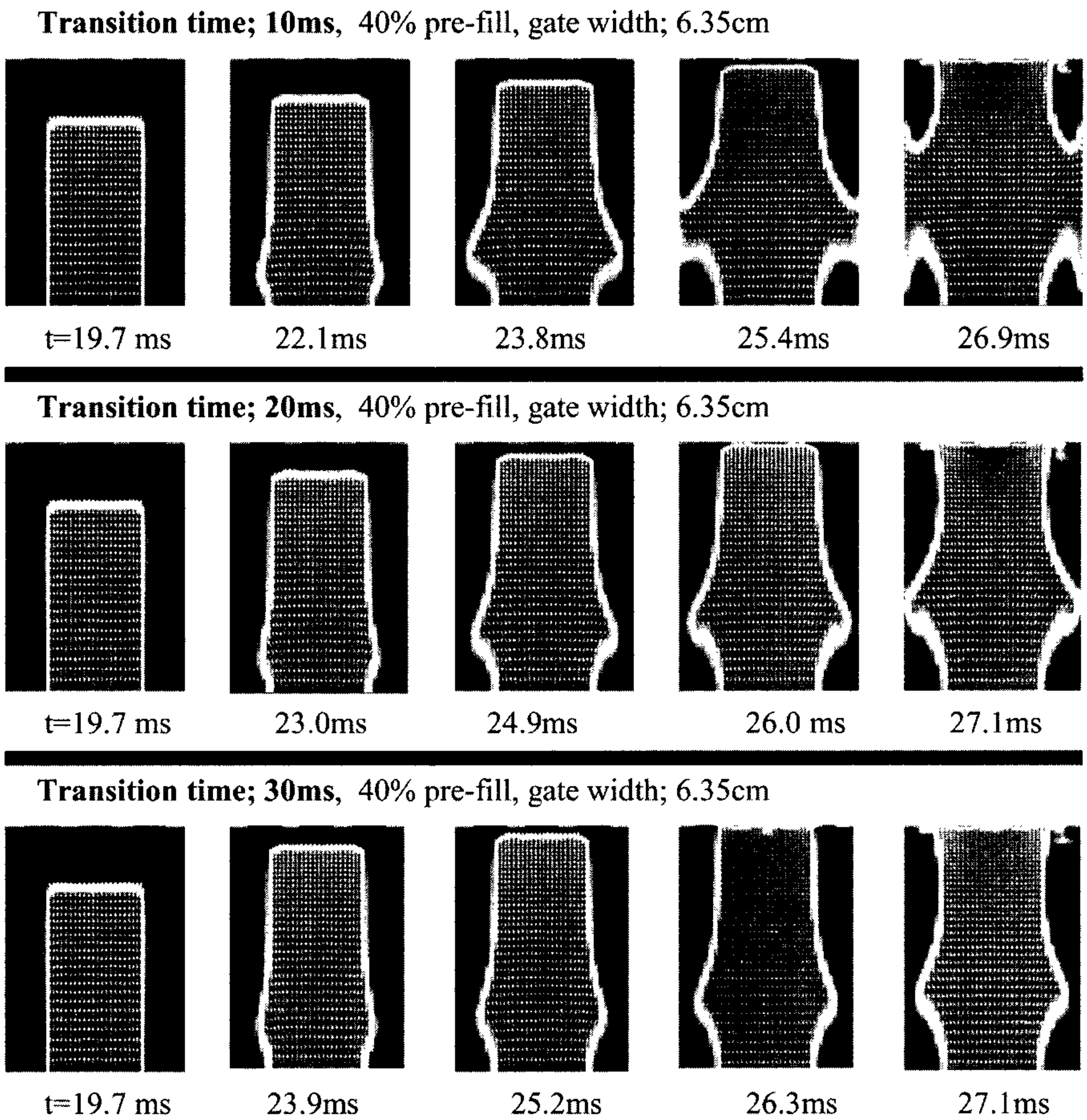


Fig. 6. The effects of transition time on filling pattern in simple die cavity

10ms of transition time turned out to be desirable to be used for the cavity geometry selected, both simple and cavity with ribs even if it does not show the best performance in all cases (Fig. 7).

4.3. Effects of Cavity Geometry

Along with cavity pre-fill percentage and transition time, cavity geometry including the design and locations of gates and vents was found to be very important parameter to be considered to achieve optimal cavity fill in terms of air entrapment. For the geometry in Fig. 6, 40% pre-fill of cavity volume seems to be too much to use with 30 ms transition time. In this case, only about 7 ms after pre-fill is completed is passed when vents are sealed with molten metal flow (i.e. about 23 more milli-second is needed to reach fast shot velocity). This relatively slow velocity (i.e. low inertia) is not enough to generate enough lateral expansion of flow.

In Fig. 7, the effect of gate width on air entrapment in the die cavity is clear. Using wider gate showed better performance minimizing air entrapment than using narrower gate width in most combinations of process parameters. In addition, it was observed that effect of cavity pre-fill was lower using wide gate width than using narrow gate width.

4.4. Effects of Slow Shot Cavity Pre-fill Velocity

To investigate the effects of slow shot cavity pre-fill

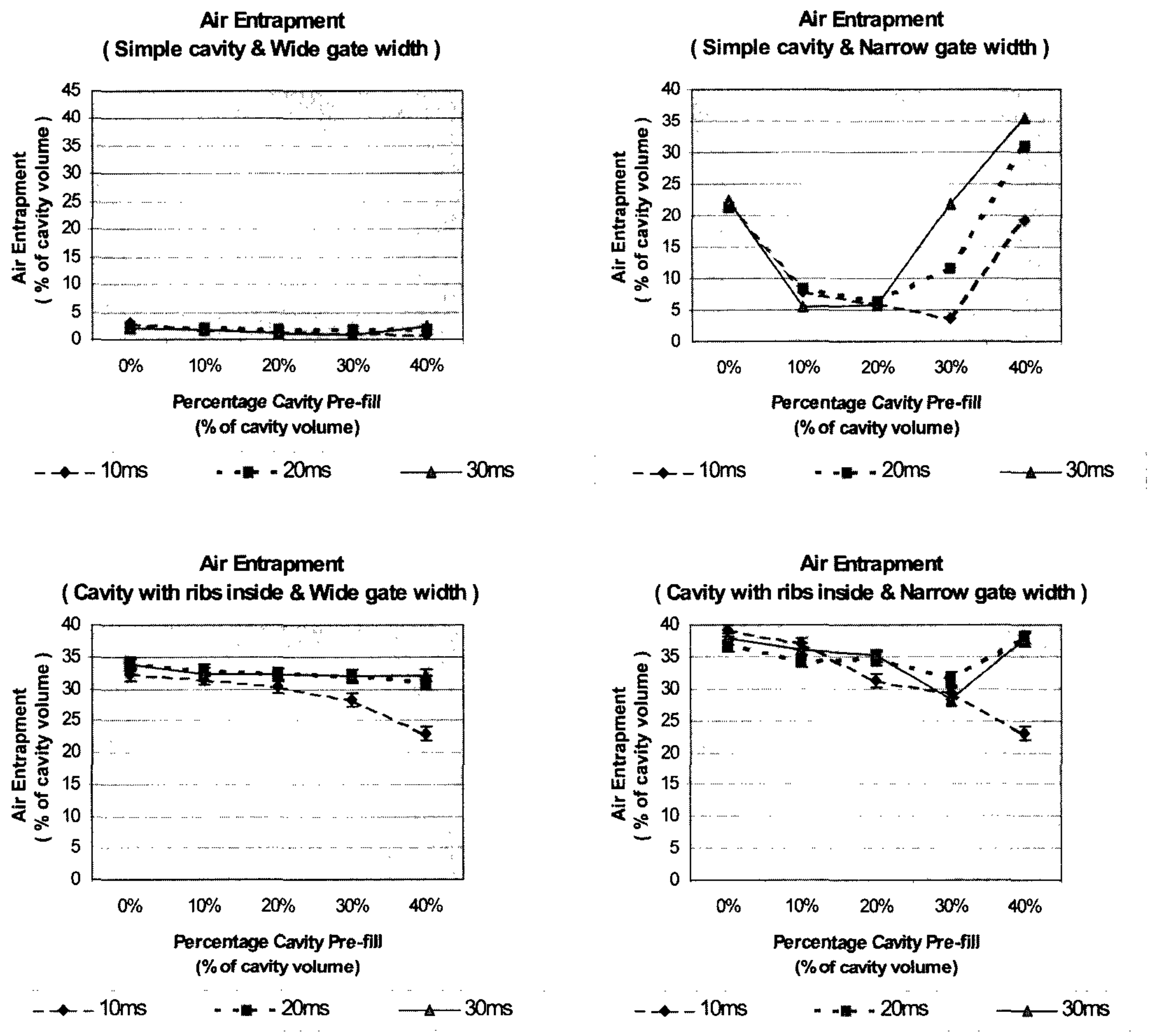


Fig. 7. The comparison of the amount of air trapped in the die cavity using different cavity pre-fill percentage and transition time for 4 different cavity geometry.

velocity, 481 cm/s of gate velocity was employed, which is 70% of the gate velocity (i.e. 687 cm/s) when plunger velocity of critical slow shot is 31.88 cm/s. As can be seen in Fig. 8, slower cavity pre-fill velocity always performed better in terms of air entrapment. Especially, larger improvement in air entrapment by using slower cavity pre-fill velocity was observed when narrow gate is used.

4.5. Optimum Values of Parameters in Terms of Air Entrapment

As shown in Fig. 7-2, in a given geometry, optimum values are found to be 10% pre-fill using 30 ms, 20% pre-fill using 20 ms, and 30% pre-fill using 10 ms even though global optimum parameter set was found to be 30% pre-fill with 10 ms transition time. Those sets of optimum value are in the manner of [pre-fill percentage + transition time =constant], constant value is 40 in this case. In another case, such as Fig. 7-4, optimum parameter sets are found to be in the similar manner with a different constant value. To visualize the optimum values of the parameters in a given geometry, smooth curve by 2D interpolation is introduced (Fig. 9-1, 9-2).

5. Conclusions

Appropriate shot parameters with cavity pre-fill can help significantly to reduce air entrapment. Even if there are difficulties to establish universal optimum values of injection parameters due to the variety of complex casting geometry, general ideas were obtained based on selected simple cavity geometry;

1. Applying cavity pre-fill approach, one physical phenomenon of flow was observed, which is lateral ex-

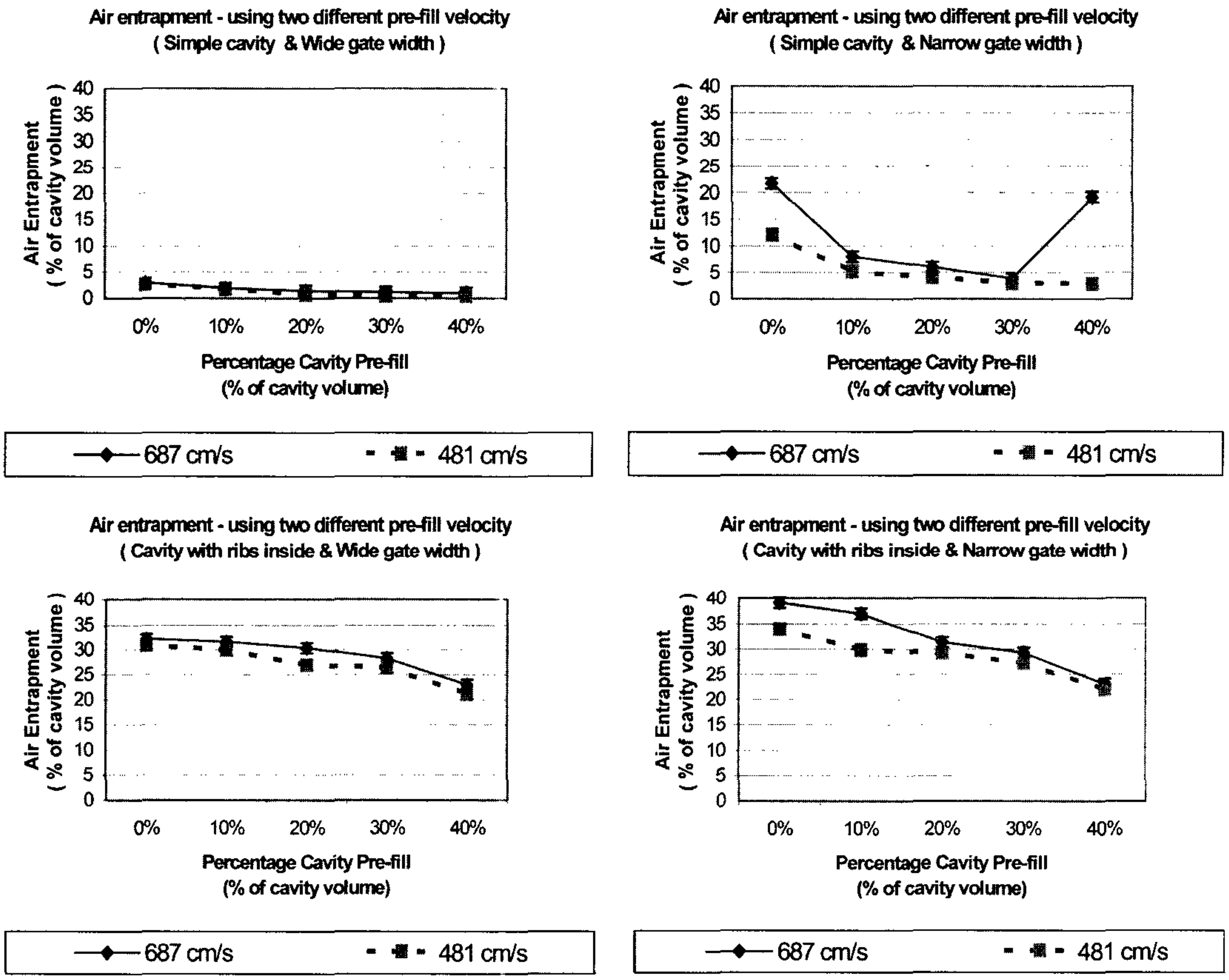


Fig. 8. Air trapped in the die cavity using slower shot cavity pre-fill velocity (gate velocity,481 cm/s, which is 70% of critical slow shot velocity) vs. critical slow shot velocity (gate velocity, 687 cm/s) [transition time: 10 ms]

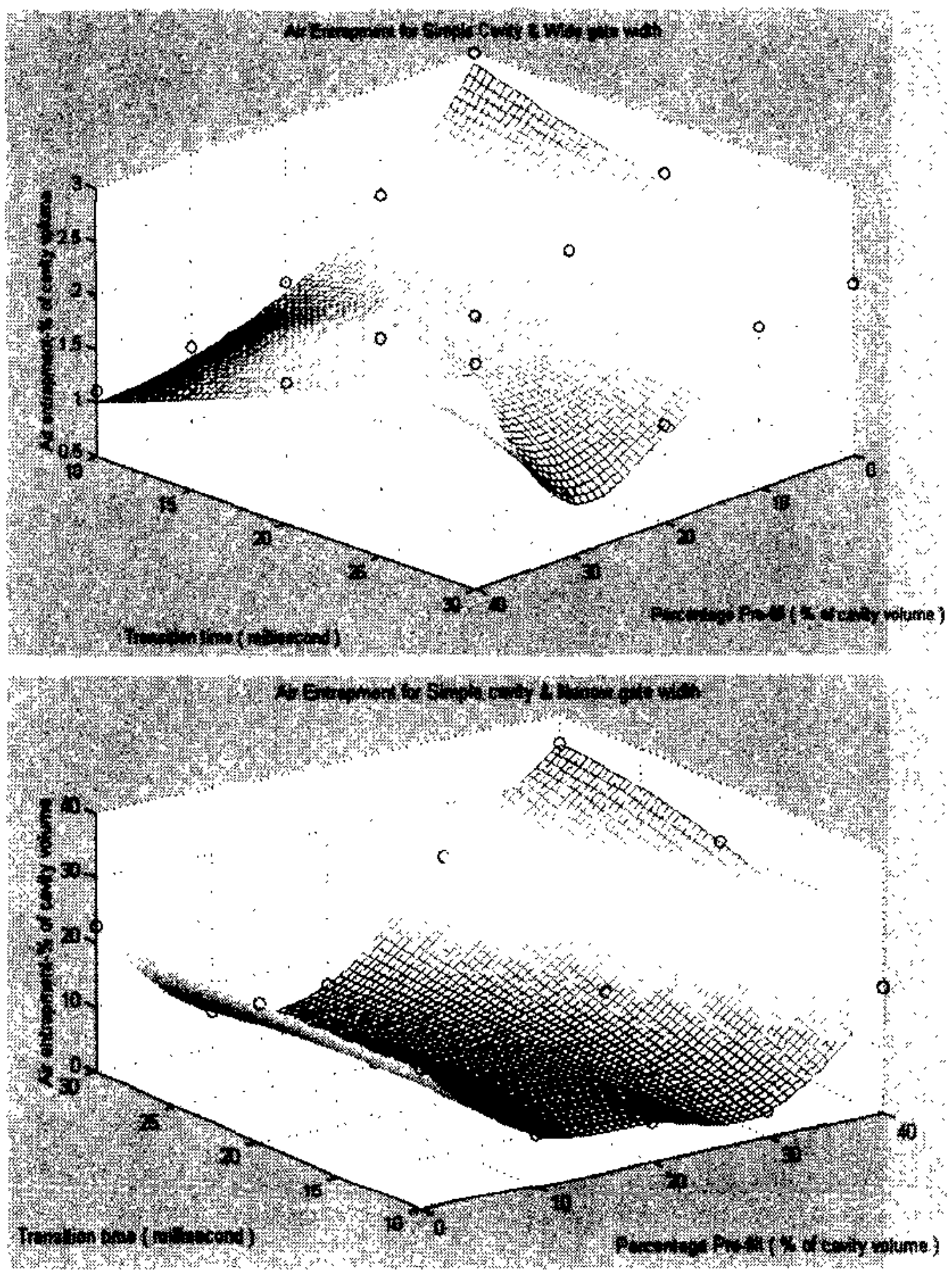


Fig.9.1. 2D interpolation (cubic) of Fig. 7.

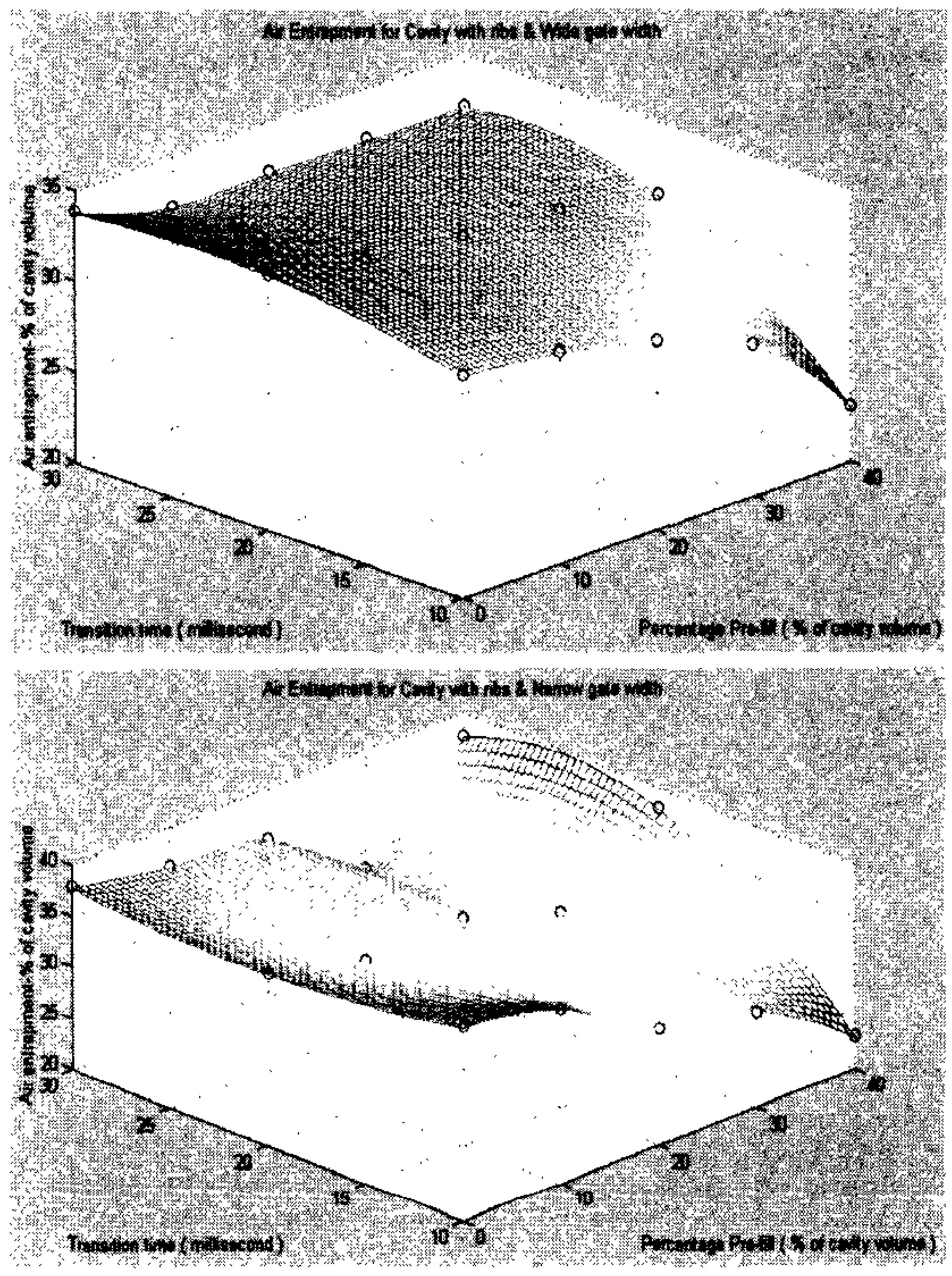


Fig.9.2. 2D interpolation (cubic) of Fig. 7.

pansion of flow due to the collision of pre-filled portion of flow and next incoming relatively fast flow. This lateral expansion of flow helps uniform filling in the die cavity unlike straightforward jet stream due to high gating velocity.

2. Selected injection shot parameters, such as cavity pre-fill percentage, transition time and cavity geometry including the location and design of gates and vents should be considered simultaneously to obtain optimum values of those parameters in terms of air entrapment since those parameters influence air entrapment interactively.

3. Slow shot cavity pre-fill velocity also effects on cavity filling patterns and accordingly, the amount of air entrapment in cavity. Slower cavity pre-fill velocity generates better cavity fill in terms of air entrapment.

4. As easily could be predicted, wide gate width generates better fill patterns in terms of air entrapment than narrow gate width (Fig. 7). Accordingly, cavity pre-fill effects are larger when narrow gate width is used.

It should be noted that as fast shot engagement (cavity pre-fill) and transition time is delayed, total cavity fill time delay is inevitable even if the method reduces the air entrapment. Therefore, cavity pre-fill can not be simply applied to a relatively thin casting part since the time delay may cause early solidification. The cavity pre-fill approach seems to be appropriate for producing thick and big automotive casting parts, such as a transmission case.

As future works, a physical simulation of water analog test and actual experimental castings are needed for the computer model validation. Also, significance test of selected shot parameters will help establish a guideline for a process design.

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