NUMERICAL ALGORITHM OF STACKED-CHIP SCALE PACKAGES (S-CSPs) ENCAPSULATION PROCESS USING FINITE DIFFERENCE METHOD

by

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"In the name of ALLAH, The Most Beneficent and The Most Merciful"

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LIST OF SYMBOLS

SYMBOL	DESCRIPTION	UNIT
English Symbols		
A_1, A_2	Pre-exponential factors	1/s
B	Exponential-fitted constant	Pa.s
C_1, C_2	Fitting constant	-
c_P	Specific heat	J/kg-K
e	Internal energy	J/kg
E_t	Total energy	J/m^3
E_1, E_2	Activation energies	K
F	Front advancement parameter	-
g	Specific gravity	m/s^2
h_{dies}	Dies height	mm
k	Thermal conductivity	W/m-K
k_1, k_2	Rate parameters described by an Arrhenius temperature dependency	1/s
m^*, n^*	Constants for the reaction order	-
n	Power law index	-
p	Pressure	Pa
r	Displacement of particle	mm
T	Temperature	K
t	Time	s
T_b	Temperature-fitted constant	K
u	Fluid velocity component in x-direction	mm/s
v	Fluid velocity component in y-direction	mm/s
w	Fluid velocity component in z-direction	mm/s
x, y, z	Cartesian coordinates	mm

Greek Symbols

α	Conversion of reaction	-
α_g	Degree of cure at gel	-
ΔH	Exothermic heat of polymerization	J//kg
μ	Viscosity	Pa.s
μ_0	Zero shear rate viscosity	Pa.s
ρ	Density	kg/m^3
τ	Shear stress	Pa
$\dot{\gamma}$	Shear rate	1/s
υ	Kinematics viscosity	m^2/s
Φ	Energy source term	J
τ^*	Parameter that describes the transition region between zero shear rates and the power law region of the viscosity curve	Pa
ξ, η, ϕ	Uniform orthogonal computational space	-

LIST OF ABBREVIATION

		PAGE
2-D	Two-dimensional	14
3-D	Three-dimensional	7
ASIC	Application specific integrated circuit	3
BGA	Ball grid array	16
C	Cross model	69
CAE	Computer Aided Engineering	16
CBS	Characteristics based split	16
CFD	computational fluid dynamic	21

C-M	Castro-Macosko model	69
CPU	Centre Processing Unit	19
CSPs	Chip Scale Packages	2
DDR	Double data rate	3
EMC	Epoxy moulding compound	4
FAN	Flow analysis network	22
FDM	Finite difference method	8
FEM	Finite element method	14
FVM	Finite volume method	14
GNF	Generalized Newtonian fluid	11
IC	Integrated circuit	1
JEDEC	Joint Electronic Device Engineering Council	3
MAC	Marker-And-Cell	22
PWB	Printing wiring board	2
RHSF	Right hand side front-tracking	57
RHSP	Right hand side pressure	51
RHST	Right hand side temperature	54
RHSU	Right hand side velocity in x-direction	52
S-CSP	Stacked-Chip Scale Package	1
SIMPLE	Semi-implicit pressure-linked equations	20
SRAM	Static random access memory	3
TQFP	Thin Quad Flat Package	18
TSOP	Thin small outline packages	18
VOF	Volume of fluid	9

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ALGORITMA BERANGKA TENTANG PROSES PENGKAPSULAN PAKEJ SKALA CIP-BERTINGKAT DENGAN MENGGUNAKAN KAEDAH PEMBEZAAN TERHINGGA

ABSTRAK

Pada hari ini, peranti-peranti mikroelektronik menjadi lebih padat, ringan dan mempunyai lebih fungsi, ini termasuklah pakej skala cip-bertingkat (*S-CSP*). Ia adalah satu teknologi yang memberi opsyen kepadatan pempakejan yang tinggi. Kebiasaannya, *S-CSP* digunakan pada produk multi-media mudah alih. Bagaimanapun, oleh kerana ia mempunyai ruang yang amat nipis dan kawasan pengisian yang luas, di mana ini akan menjejaskan kualiti pengisian seperti kelompangan, kerencatan aliran, dan ketidakseimbangan bentuk aliran. Di dalam kajian ini, satu penyelidikan tiga-dimensi (3-D) aliran acuan semasa proses pengkapsulan *S-CSP* dipersembahkan. Kaedah pembezaan terhingga (*FDM*) berasaskan persamaan *Navier-Stokes* telah dimajukan untuk menganalisa aliran di dalam rerongga acuan. Model reologi polimer dengan kesan pematangan (model *Castro-Macosko*) dan tanpa kesan pematangan (model *Cross*) digunakan di dalam model aliran bendalir. Selain daripada itu, kesan kepelbagaian ketinggian dai dan halaju masukan juga turut dikaji. Konsentrasi-palsu dengan bersandarkan teknik penjumlahan bendalir (*VOF*) digunakan untuk menjejaki aliran hadapan pada sela masa tertentu. Untuk pengesahan model 3-D ini, perbandingan di antara keputusan berangka dan keputusan eksperimen telah dibuat. Keputusan berangka mempamerkan keserasian yang baik dengan keputusan eksperimen yang diperolehi. Keputusan-keputusan analisis juga menunjukkan sedikit masa yang diperlukan untuk pengisian penuh sesuatu pakej jika halaju masukan ditingkatkan. Akan tetapi, ia memberi kesan terhadap peningkatan kelompangan. Keputusan-keputusan daripada model reologi *Castro-Macosko* lebih menunjukkan kesesuaian terhadap aliran reologi sebenar. Selain itu, ketinggian dai memberi kesan kepada penambahan masa

pengisian pakej. Ia juga menyebabkan ketidakseimbangan aliran acuan berlaku. Manakala mekanisme lompangan juga dapat diperhatikan terhasil daripada ketidakseimbangan aliran acuan. Akhirnya, didapati bahawa halaju masukan pada 2 mm/s dengan ketinggian dainya dikurangkan di dalam rerongga acuan, dan penggunaan model reologi Castro-Macosko dapat memberi pengisian acuan yang optimum.

NUMERICAL ALGORITHM OF STACKED-CHIP SCALE PACKAGES (S-CSPs) ENCAPSULATION PROCESS USING FINITE DIFFERENCE METHOD

ABSTRACT

Nowadays, microelectronic devices become more compact, lighter in weight and more functional, including Stacked-Chip Scale Package (S-CSP). It is a technology which has high density packaging options. The S-CSP is widely adopted in portable multi-media products. However, it has thin space and wide filling area, which has become quality concern such as voids, unbalanced flow, and retardation flow pattern. In this research, a study of three dimensional (3-D) mould flows during encapsulation process in S-CSP is presented. A finite difference method (FDM) based on the Navier-Stokes equation has been developed for the flow analysis in the mould cavity. Polymer rheology models with curing effect (Castro-Macosko model) and without curing effect (Cross model) have been used in the fluid flow model. In addition, the effect of variables of die thickness and different inlet velocities has been studied. Pseudo-concentration which is based on the volume of fluid (VOF) technique was used to track a melt fronts for each time step. In order to verify this 3-D model, the comparison of the numerical results and experimental results has been made. The numerical results show good agreement with experimental results. The results also shown that the time taken to fill the package decreased when the inlet velocity was increased. As a consequence, the risk of getting voids was also higher. The results from the Castro-Macosko rheology model were closed to the actual flow rheology. The thicker the die thickness, the more time is needed to fill the package. Thicker die thickness was also found to cause the unbalanced flow. A void mechanism is also observed due to unbalance flow of the mould compound. Finally, it was found that for the optimization of mould filling, the inlet velocity should be 2 mm/s with lesser die

thickness in the mould cavity. In addition, the Castro-Macosko rheology model should be used.

CHAPTER 1

INTRODUCTION

1.0 Overview

At the first sub-chapter, an Introduction to the electronic packaging, integrated circuits (ICs) and Stacked-Chip Scale Packages (S-CSP) will be reviewed. For the next sub-chapter, it will discuss about encapsulation background and problems follow by the significance of the study mould filling. The remainder sub-chapter will explain the problem statement, objectives of the study and scope of research works before ending by the outline of the thesis.

1.1 Introduction to the electronic packaging, integrated circuits (ICs) and Stacked-Chip Scale Package (S-CSP)

Electronic packaging is defined as 'a package to house a silicon chip in an electronic system to provide both the environment necessary to endure the proper function and reliability of the chip, and a means by which the chip can be electrically connected to the system' (Choi, 2005). As such, the electronic package is an integral part of the microelectronic system. Typically the microelectronic refers to the micro devices of electronic product measured in micrometers (μm) such as integrated circuit (IC). IC is an integration of many such circuits or components such as transistors, resistors, inductors, capacitors, etc to form functional circuits on a single chip. The main functions of an electronic package are to protect the electronic components from adverse environmental and mechanical effect besides providing a structural support and electrical insulation. Moreover, it also provides heat dissipation, signal timing and power distribution.

Integrated circuits (ICs) are processed on a large piece of semiconductor substrate call 'wafer'. Starting with wafer preparation process, silicon is purified and prepared into wafers. After that, microchips are fabricated in a wafer fab. Wafer sizes normally can vary from 3 to 12 inches in diameter and there are may be hundreds to thousands of ICs on a wafer. Each die is probed and electrically tested to sort for good or bad chips. The wafer enters a wafer dicing process and it will cut by a fully automatic dicing saw whose blade is tipped with diamonds. Individual ICs or chips are the result at the end of the dicing process. Thus a piece of semiconductor material is transformed into a functional microelectronic part. To be able to use those ICs, they have to be packaged, tested and assembled on the system board (Quirk and Serda, 2006). Figure 1.1 below describes the entire fabrication process of forming a system from the wafer preparation.

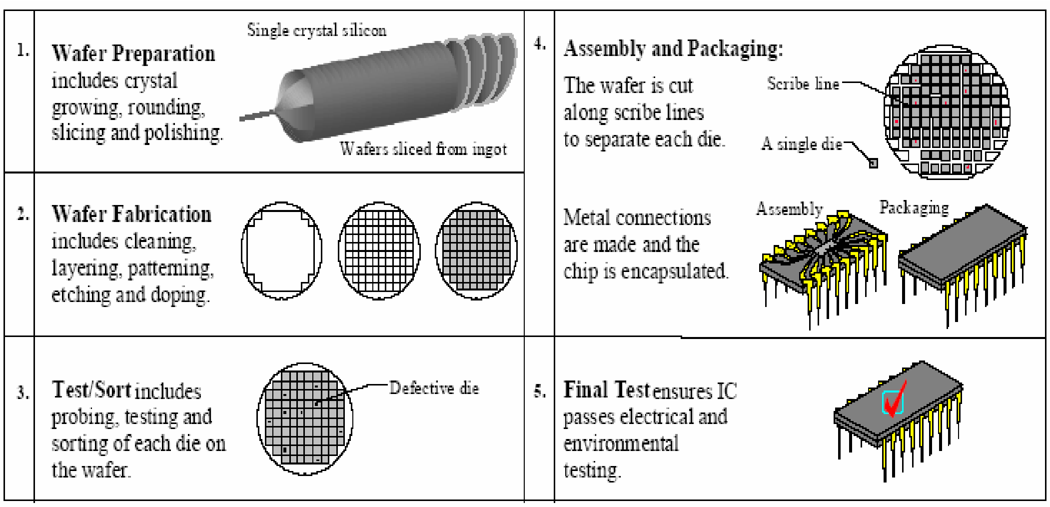


Figure 1.1 Schematic of integrated circuit (IC) fabrication process (Quirk and Serda, 2006)

IC packages can be classified into two categories; through-hole packages and surface mount packages. If the packages have pins that can be inserted into holes in the printing wiring board (PWB), they are called through-hole packages. If the packages are not inserted into PWB but are mounted on the surface of the PWB, they are called surface mount packages. One of the surface mount packages is Chip Scale Packages (CSPs). The CSPs is a package whose area is less than 1.2 times the area of the IC. A CSP component can very well be manufactured in the BGA format. Figure 1.2 shows the wirebonding technique when building a CSP component. A rigid board or a flex film is normally used as a carrier for the chip. The chip in the upper component is attached to the substrate using wirebonding. It packages has smaller, thinner and lighter characteristic (Tummala, 2001). It has been developed to address the demands of modern electronics. The pace of CSP technology development is accelerating rapidly in the semiconductor industry driven by the broad adoption of CSPs in wireless handsets and handheld electronics.

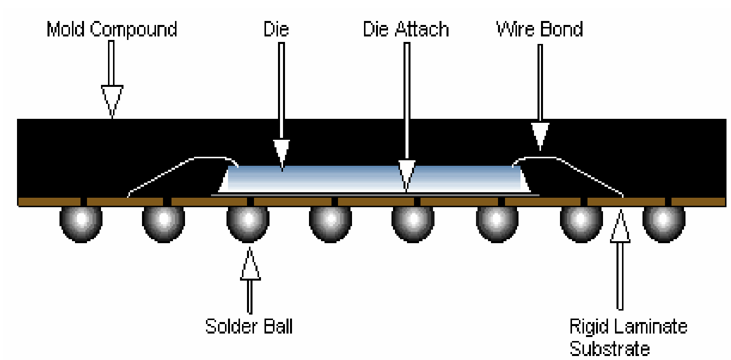
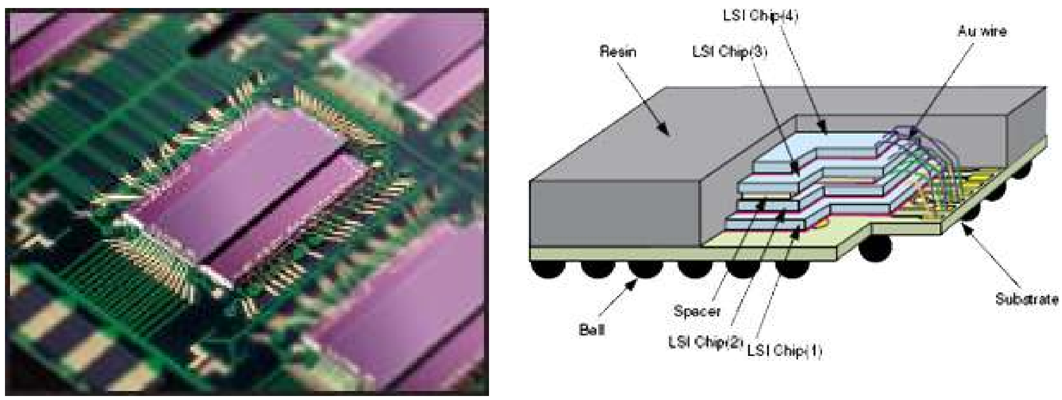


Figure 1.2 Build up of a typical CSP (www.amkor.com)

However, based on the current scenario requires a maximum functional integration in the smallest footprint, lowest profile and low-cost packaging (Fukui *et al.*, 2000). Therefore Stacked-Chip Scale Package (S-CSP) is introduced. It integrates an application specific integrated circuit (ASIC) and memories such as flash, static random access memory (SRAM), and double data rate (DDR) into one package by stacking probed good die, interconnecting them with wirebonding and moulding all into one Joint Electronic Device Engineering Council (JEDEC)-standard package. JEDEC is a body mandates standard dimensions for the most common types of packages irrespective of who manufactures the package. Easily to say, S-CSP enables the stacking of a wide range of different die in the same package (Zhou and Gerber, 2004). This broad high volume infrastructure enables the rapid deployment of advances in die stacking technology across multiple products to achieve lowest total cost requirements. Stacked CSP is the outcome of market demand for greater compactness and lighter weight in portable multi media devices such as cellular telephones, digital cameras, PDAs and audio players. Figure 1.3 below shows two examples of Stacked-Chip Scale Package (S-CSP).



(a) (b)

Figure 1.3 Stacked-die package (a) a snapshot of S-CSP (www.amkor.com) and (b) S-CSP with four die (chips) with a spacer (www.renesas.com)

1.2 Encapsulation background and problems

Encapsulation is a famous technique in protection and is widely used in integrated circuit (IC) packages. The most common encapsulation process normally can be classified into two categories which are transfer moulding and liquid encapsulation. Transfer moulding of epoxy compound is the most popular because of its capability to mould small parts with complex features. Epoxy moulding compound (EMC) is preheated before being loaded into transfer port. Transfer port is the cylinder which receives the moulding compound initially. By applying pressure, the heated molten moulding compound is transferred from a port through a runner that lays parallel to the strip cavity set. It feeds the moulding compound to each cavity through small entrance ports called gates. Figure 1.4 shows a schematic of the bottom half of productions mould with a short runner feeding a set of eight cavities. Also shown with some of the typical ingredients in its formulation is one epoxy pellet being compressed by the transfer plunger and Figure 1.5 depicts the typical transfer moulding process.

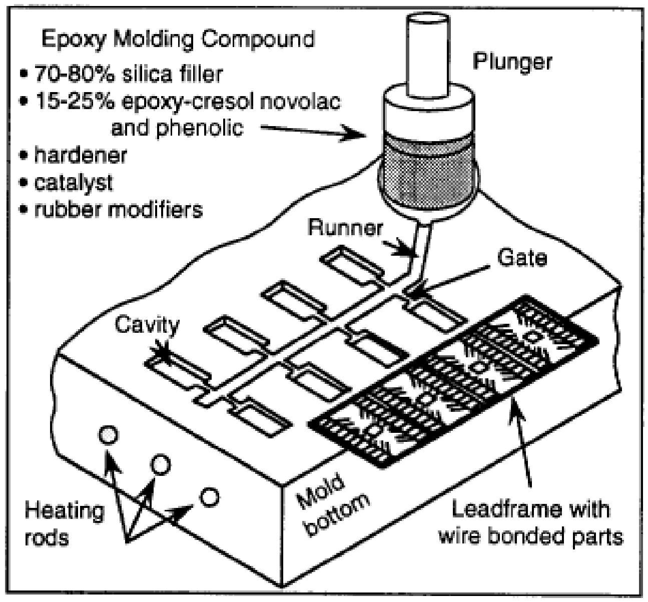


Figure 1.4 Transfer moulding process with epoxy moulding compound pellet being loaded into the pot prior to moulding (Nguyen, 1993)

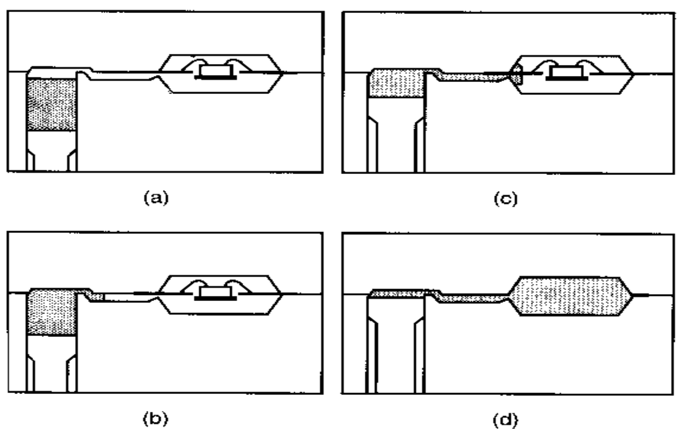


Figure 1.5 A typical transfer moulding process (Tummala, 2001)

Although transfer moulding is a mature technology, it is still difficult to optimize. The moulding defects such as package cracking, package stress-related electrical failure, wire- sweep, package voids and pits, incomplete filling (short shots), blistering, package delaminating, excessive flashes, solder voids and mark permanence failure should be removed in order to gain the moulding quality (Manzione, 1990: Tummala, 2001). Design of the mould used in the process is a costly and lengthy process. The prototypes are expensive because each piece of tooling must be designed, machined and tested in a very short amount time. For example, prototype often requires numerous modification and rework. Repeated moulding tests should be done if the desired process does not meet to the requirement. To minimize the impact of these problems beside for better mould design and optimization process, numerical flow analysis during the encapsulation process is needed (Nguyen, 2000). Based on this scenario, there are many software that have been developed for mould filling process such as Moldex-RIM®, Moldflow®, PLICE-CAD®, InPack®, etc. Figure 1.6 indicates the simulation sample of predicted melt front advancement applied by Pei and Hwang (2005) in their studies of IC encapsulation process.

Figure 1.6 Predicted melt front advancement at different time steps using Moldex-RIM® software (Pei and Hwang, 2005)

1.3 Significance of the study of mould filling

S-CSP is a high density packaging technology which accelerates the semiconductor industry. This is driven by broad adoption of S-CSP in portable multi media products. The technology provides two or more die stacking in a single package. This will provide better performance and cost reduction to the end user.

However, it becomes concern to the package quality. Most of the S-SCP mould is the matrix array type with thin space and width filling area which lead this matter become worse. There are several factors that can affect the mould filling yields, such as die thickness, size and array arrangement of complicated stacking dies. There are defined as critical factors at initial stage of product quality planning (Sze and Papageorge, 1998). It is reported that the industry attempts to produce the thinner packages with more stacked die.

Besides those challenges imposed by the structural complexity, the nature of moulding compound should be reviewed (Lee *et al.*, 2006). EMC is reactive during the transfer process. The kinetics of the curing reaction will influence the degree of conversion of the moulding compound and also effect on the rheological behaviours of the resin flow. It involves complex non-Newtonian fluid flow, coupling heat transfer and chemical reaction. Moreover, these phenomena in the complex mould geometry make it difficult to analyze the process and to further optimize the design. As a result, problems such as voids, retardation flow, and unbalanced flow occurred.

Referring to the complicated phenomena and interplay of those variables encountered, analytical methods seem impossible to solve this process. Therefore, this thesis will present a three dimensional (3-D) mould filling analysis using finite difference method to predict and simulate the mould flow process in S-CSP. This is an alternative method to investigate the possible solution to those problems mentioned in the previous paragraphs.

1.4 Problem statement

Encapsulation has become an important process in microelectronic industry. In fact, there are a number of common moulding-related failure mechanisms such as voids, air trap, retardation flow, and unbalanced flow. Recent advances in IC packaging for example moulded array package technology with overhang stacking dies namely Stacked-Chip Scale Package (S-CSP). The more the stacking, the better the performance. However, it has increased the risk of defects and imposed even more demanding requirements on moulding process and on the material formulation. At the moment, there are extremely limited literature reviews on this field. Lee *et al.* (2006) were the first to use Castro-Macosko model which used only die height of three stacks, together with FVM. They also used variable gate position with constant inlet velocity. This research was the first which utilized both Castro-Macosko model and Cross model which applied die height up to seven stacks, with the use of FDM. In contrast, the gate position was constant while the inlet velocity was variable. In addition, compared to FVM used by Lee *et al.* (2006), FDM is relatively efficient and simple numerical method for solving partial differential equations.

1.5 Objectives of the Study

The present study has four main objectives as mentioned below:

1. To develop a numerical code using the finite difference method (FDM), non-isothermal and incompressible flow to analyse of mould filling for three-dimensional (3-D) flow in S-CSP.
2. To study the effect of inlet velocity at mould gate on the mould filling process.
3. To study the effect of the polymer rheologies using Cross model and Castro-Macosko model on the mould filling simulations.
4. To study the effect of die thickness on the fluid flow field.

1.6 Scope of Research Works

In this research work, the simulation of 3-D fluid flow is focused on generalized Newtonian fluid (GNF) by considering only two different approaches in calculating polymer rheology; Cross and Castro Mocascko Models. This research also concentrates on filling time, effect of inlet velocities and die thickness of the packages in order to predict the mould flow process in the S-CSP. The results will be viewed on top surface for clarifying the comparison of the melt fronts. Bear in mind, the present work does not involve the analysis of wiresweep during mould filling process. Volume of fluid (VOF) with pseudo concentration was used to track the melt front of the epoxy moulding compound (EMC).

1.7 Thesis Outline

There are five chapters in this thesis. In chapter one, brief presentation about IC packaging, background, significance, objectives and scope of research are introduced. In chapter 2, literature studies of mould flow in IC encapsulation are presented. Methodology approach in mathematical modelling and numerical method has been highlighted in chapter 3. In chapter 4, comparison of experimental results and simulated results are presented. The discussion also has been extended for other cases such as the effect of die height, different inlet velocities and different rheology approach. Finally, conclusion and recommendation for future works will be discussed in chapter five.

CHAPTER 2

LITERATURE SURVEY

2.0 Overview

For the first sub-chapter, a brief introduction about mould filling is presented. The second sub-chapter reviewed the epoxy moulding compound (EMC) rheology factors that affected the polymer flow. The fluid flow model and front tracking become the next sub-chapter to be reviewed. The summary of the literature reviews is given at the end of this chapter to support the simulation work that has been done in this study.

2.1 Introduction

A fluid flow phenomenon during encapsulation process has been studied by both experimental and numerical methods. It becomes more adorable in accordance with the high popularity of electronic products.

The most common moulding defects in transfer moulding process are short-shot, flashing, resin bleeding, air trap, wire-sweep, paddle shift and stress-induced problems as mentioned by Manzione (1990) and Tummala (2001). Recent advances of IC packages such as fine pitch wire-bonding (Nguyen *et al*., 2000), moulded array package technologies, and imposed even more demanding requirements on the moulding process and on the material formulation will increase the risk of defects (Nguyen *et al.*, 1997:1998). Furthermore, it becomes more complicated for stacking dies in the moulded array packages; at the same time lead the wire-bonding to be more fibrous (Lee *et al.*, 2006).

Therefore, flow analysis has been identified as an approach for optimization of processing and better mould design of transfer moulding (Han and Wang, 2000). From the engineering aspect, a bind up of complex non-Newtonian fluid flow couple with heat transfer as well as chemical reaction during encapsulation process. It can be said, analytical solution seem impossible to track this process. Therefore, Computer-Aided Engineering technique can be manipulated to analyse the problems. Turng and Wang (1993), Han and Wang (1995), and Nguyen (1993) are the pioneers of numerical simulation of the flow during IC encapsulation process. Their research has attracted many researchers worldwide to get involved into this area.

2.2 Generalized Newtonian Fluid

A generalized Newtonian fluid (GNF) is defined as a purely viscous fluid. That is its viscosity depends only the shear rate or shear stress (Carreau *et al.* 1997). In many flow situations, visco-elasticity will not play an important role and the non-Newtonian viscosity is sufficient to describe the rheology of the material. Viscosity versus shear rate data are usually represented on log-log plots as shown in Figure 2.1. The simplest viscosity model, the Newtonian (one-parameter model would be represented by a horizontal line in this figure). That is, the viscosity, μ is given by the constant value. Clearly, the typical behaviour depicted in the figure suggests the need for a more realistic viscosity model. Most polymeric materials show Newtonian behaviour at very low shear rates. High-molecular weight polymers often show shear thinning behaviour in that their viscosity decreases with increasing shear rates providing the pseudo plastic portion of the curve. At very high shear rates, there is usually second upper Newtonian plateau (Manzione, 1990). Quite a variety of non-Newtonian viscosity models have been introduced. However, only two models have been applied for this study. There are Cross rheology model and Castro-Macosko rheology model. The reason of using the Cross rheology model since it is widely established for general polymer rheology. Instead of the Castro-Macosko rheology model, it is specifically used in thermoset polymer rheology.

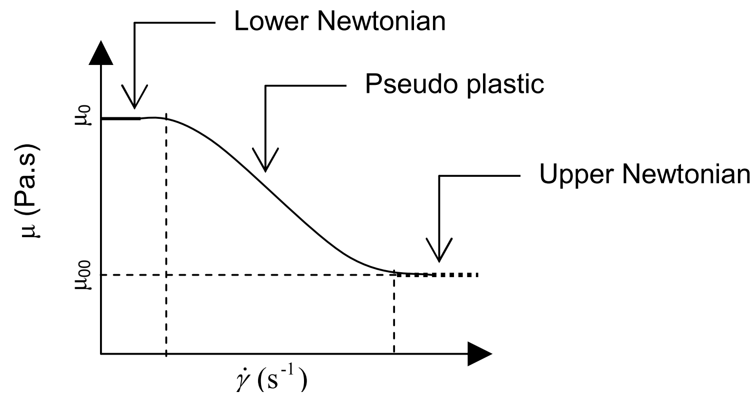


Figure 2.1 Sketch of viscosity-shear rate data (log-log plot) as well as predictions of some viscosity model.

2.2.1 Cross rheology model

Cross model was proposed by Cross in 1965 (Carreau *et al.* 1997). He used Arrhenius temperature dependence to describe the viscosity of the polymer. For engineering applications, the Cross model is the most frequently used three-parameter GNF model. The parameters are μ_0, τ^* and n and the detail of this model will be discussed in Chapter Three. Han and Wang (1995), Fox *et al.* (1998) and Chang *et al.* (2004) among the researchers which used this model. They expressed that the generalized Cross viscosity model gave a good data fit of viscosity and showed to provide a pertinent material model for mould filling analysis.

2.2.2 Castro-Macosko rheology model

An alternative model is Castro-Macosko model. It was proposed by J. M. Castro and C. W. Macosko in 1980 as reported by Nguyen (1993). This model has the advantage of taking consideration about curing reaction of the moulding compound. Since many of the polymer materials used in electronic packaging are thermoset polymers, this Castro-Macosko model uniquely suited this need because they (thermoset polymers) polymerized to a thermally intractable material from low viscosity starting resin. This polymerization process is often termed as curing. The Castro-

Macosko model is the high successful five-parameter GNF model. The parameters are μ_0, τ^*, n, α and C. The detail explanation of this model will be discussed further in Chapter Three.

Several researchers have studied on the Castro-Macosko rheology model to be used in rheology model of the EMC. Nguyen (1993), Tanaka *et al.* (1994), Bidstrup-Allen *et al.* (1997), Chang *et al.* (1998) and Nguyen *et al.* (1999) are the examples of the early researchers who have studied on this model. Nguyen (1993) found that the Castro-Macosko model is the best description of the epoxy viscosity behaviour. According to Bidstrup-Allen *et al.* (1997), the success to-the-point of the flow simulation is strongly dependent on the input information related to the cure kinetic and rheology of the moulding compound. Nguyen *et al.* (1999) also agreed that a successful simulation required on precise prediction of both the cure and rheology of the moulding compound.

2.3 Numerical fluid flow models of moulding compound

2.3.1 Introduction

A numerous research efforts have been carried out in fluid flow simulation during encapsulation process for various package designs ranging from wire bonding, chip carrier with beam leads to direct chip connection.

The earliest model used was a Hele-Shaw approximation. Basically, the Hele-Shaw cell consists of two flat plates that are parallel to each other and separated by a small distance. The Hele-Shaw approximation uses gapwise-averaged mass and momentum-conservation equations ignoring the gapwise component of the flow. The assumptions of Hele-Shaw approximation are the thickness of the model is relatively small as compared to its width and length and viscous effect dominates the flow. Thus, the inertia effect is negligible (Wai, 2003). It includes continuity equation, momentum equation and energy equation. In continuity equation, mostly the incompressible fluid takes account. The momentum equation in x and y directions can be obtained. A simple uniform pressure is used in the gapwise direction for the z direction. The same method will be repeated into energy equation. This approximation commonly used in two-dimensional (2-D) model.

Instead of the Hele-Shaw approximation, Navier-Stokes equations are the fundamental partial differentials equations that describe the flow of fluids. The Navier-Stokes equation is obtained by combining the fluid kinematics and constitutive relation into the fluid equation of motion. The flexibility of Navier-Stokes equations, it can be applied either in 2-D or in 3-D purpose. The Navier-Stokes equations can also be solved by using Finite Element Method (FEM), Finite Volume Method (FVM) and Finite Difference Method (FDM).

2.3.2 Two-dimensional (2-D) model with Hele-Shaw approximation

Hieber and Shen (1980) developed a flow model for non-Newtonian fluid under non-isothermal conditions. They employed finite element for planar coordinates while finite difference used for gapwise and time derivatives. Hieber *et al.* (1983) extended their flow model into various gap thicknesses. The modelling is still based on previous approach but includes the effects of viscous heating and conduction upon the flow dynamics.

Turng and Wang (1993) and Nguyen (1994) have attempted to analyze the EMC flow during encapsulation process numerically. The behaviour of the EMC was described by a generalized Newtonian fluid model. Elementary of the geometry in the chip cavity is very complicated, analysis was carried out for a simplified geometry by treating the leadframe as a solid and neglected the cross flow through the opening in the leadframe.

Continues effort has been made by Han and Wang (2000) by applying a finite element method (FEM) for the flow analysis in the mould cavity. The first effort is to analyze mould flow during the filling and post-filling stages. The second effort is to analyze the mould flow in the chip cavity through the openings in the leadframe. They proposed two approximated models to calculate the flow through the opening in the leadframe. For the first method, the flow through the leadframe opening has been modelled as a source term in the continuity equation. For the second method, the cross flow elements that physically connected the lower and upper cavities were used to account for the cross flow. The thickness of the cross-flow elements has been determined using analytical equations for the pressure drops during flow through openings.

Tanaka *et al.* (1994) studied the void phenomena by both experiment and simulation. Some conclusions have been made; the raw epoxy with high viscosity and slow transfer speed has the advantage of reducing voids. Chai *et al.* (2000) carried out with the application of mould flow simulation to predict the unbalanced flow in various package designs. They found that the cavity thickness, lead frame design and surface roughness affect the flow behaviour and causes air trap and void problems.

Beyerlein and Hornberger (2001) investigated the flow under incompressible, non-isothermal conditions and symmetric thermal boundary conditions using FEM software to study on linear and elastic wire deformation for optimizing production cost. In other case, Lee *et al.* (2003) attempted to evaluate various design configurations using the same software. They imposed the Taguchi method to minimize manufacturing variability. They concluded that Taguchi method can give clearly what are the factors that affect the flow balance for mould flow analysis.

Liang *et al.* (2005) and Kulkarni *et al.* (2006) developed a FEM for Newtonian fluids. The first researcher herded into transfer moulding and assumed the process is isothermal. They found that the filling time for a flow can be improved by increasing the gate thickness, gate length, gate width and by decreasing the runner thickness, runner width and flow velocity. The difference carried by the second researcher is underfill process, non-isothermal and characteristics based split (CBS) scheme applied. The advantage of CBS scheme is easy, straightforward and takes less computational time.

A new methodology presented by Jong *et al.* (2005) in doing Computer Aided Engineering (CAE) moulding simulation by controlling the shape factor owing to consider the effect of wire density that cause the flow resistance and applied non-Newtonian fluids under non-isothermal conditions for the high pin-count ball grid array (BGA) packages. The results showed a better solution for both cases; melt front advancement and wire-sweep prediction and concluded that a new method gave a better solution for melt front advancement and wire sweep prediction.

A good pioneering work on matrix array of die was done by Sze and Papageorge (1998) outlined with mould flow simulation followed by the actual process. They noted that three significant factors; die thickness, die size and die array arrangement are very important because they may effect encapsulation process yield as a result of thin mould and large mould cavity size requirement. They also carried out that thinner die can reduce encapsulation voiding and balance flow front.

However, it is reported that the Hele-Shaw approximation has a limitation due to ignorance of the gapwise component of the flow. Han *et al.* (2000) stated that the problems of paddle shift due to pressure difference across the paddle cannot be predicted accurately. Su *et al.* (2000) shared a same view that the fluid dynamic characteristics in the thickness direction are important for the paddle shift and wire sweep cases. Kim and Turng (2004) noted that the Hele-Shaw flow formulation also omits calculation of velocity component and thermal convection in the gap-wise direction; heat conduction in the planar directions of the thin cavity and the fountain flow behaviour, viscous convection and heat conduction on the lateral wall surfaces are also neglected. Furthermore, it also has difficulties to predict accurately the melt flow behaviour in such three-dimensional regions as melt fronts, weld lines, bosses, corners, ribs, areas with sudden thickness change and also for part which has complex geometries. Shen *et al.* (2005) also explained the shell element used in the Hele-Shaw model needs the construction of mid-plane which is time consuming.

2.3.3 Three-dimensional (3-D) model

Wu *et al.* (1996) introduced a three-dimensional modelling for the simulation of wire sweep during cavity filling in transfer moulding of IC packaging incorporating resin cure. However, their finite element method (FEM) bases have some limitation. The flow across the leadframe between the top and bottom halves of the cavity is negligible and the fluid is steady flow model that ignored the presence of the flow front.

Haagh and Vosse (1998) developed a finite element program to solve Newtonian fluid in two-dimensional (2-D) and three-dimensional (3-D) to simulate the mould filling processes. The flow was considered incompressible and isothermal. Hence, the Navier-Stokes equations are defined from the conservation equations of mass and momentum. In addition, a fictitious fluid was introduced to represent the air inside the cavity for melt front tracking purposed and the model also is able to simulate the fluid flow phenomena, fountain flow effect.

Nguyen *et al.* (1999) simulated the flow of a commercial EMC by computing the temperature, pressure, velocity, and cure fraction. In order to avoid the grid size escalated out of control and required excessive amount of computer times, they simplified the model by modifying and omitting some certain features. The simulation results showed only partial agreements with the actual process. The assumptions made are lack of details in the model and its size is limited such as the wirebonds are omitted. For these reasons, the flow is retarded near the die and determined the overall shape of the flow front. Other reasons such as constant fill rate and incompressible compound also contributed to the flow divergence to the flow fronts.

Han and Gupta (2000) imposed the Stokes flow equation for an inertia-free, viscous, incompressible flow under isothermal condition based on finite element methods (FEM). They proved that the normalized thickness difference can give significant effect on weld line and paddle shift. Han *et al.* (2002) extended their studies to the effect of non-isothermal and incorporated into the fluid front advancement simulation by coupling the energy equation with mass and momentum conservation equations. The curing effects of the EMC on fluid flow also have been considered seriously by inserting the heat generation in the analysis. They successfully predicted melt front advancement and pressure variation are in good agreements with the experimental results.

Su *et al.* (2000) developed a simplified three-dimensional model of thin small outline packages (TSOP) that flow behaviour in the thickness direction could be taken in computation to simulate the moulding process and then predict the paddle shift in an acceptable accuracy. The assumption of simulation is laminar, isothermal and Newtonian fluid. They found that the simulation gave more accurate results than Hele-Shaw approximation to predict the fluid mechanical behaviour of the filling process.

Nguyen *et al.* (2000) has carried out the computational modelling and validation on the encapsulation of plastic packages by transfer moulding of a 144-lead Thin Quad Flat Package (TQFP). The comparison has been made for the pressure, temperature and flow front advancement in the cavities and runners for validation of the newly developed software. They separated three models; first two models represented the die as a single rectangular box centred but in different thickness of the die and the third model included leadframe and other details. The parameters conditions were set from experimental data.

Kim and Turng (2004) came out with the complete 3-D approach, more accurate predictions of physical quantities and better representation of melt flow behaviour during the filling and packing stages can be expected. In order to prove the capabilities of 3-D, they presented a number of illustrative examples of 3-D simulation based on FEM and its differences between predictions from the 2.5-Dimensional Hele-Shaw approximation and 3-D analyses.

Zhou *et al.* (2005) developed a 3-D finite element model with assumption as incompressible, purely viscous and employed an equal-order velocity-pressure interpolation method. The velocity in the gap-wise direction is not omitted and the pressure also varied in this direction. They found that the 3-D simulation model is capable to simulate accurately of thick or non-uniform-thickness parts and successfully prediction some flow behaviour such as speedway and fountain flow.

Even 2-D and 3-D FEM model can provide major advantages in treating complex geometries and irregular boundaries but for the simulation results, it would takes significant times and large memory space as reported by Kim and Turng (2004), Haagh and Vosse (1998) and Nguyen *et al.* (1999). The problem became worse if it is implemented in the large-scale memory 3-D applications and conventional FEM needs too much Centre Processing Unit (CPU) time as notified by Chang *et al.* (2004).

An alternative method of switching from the 3-D ordinary technique which based on FEM to finite volume method (FVM) has been made by Chang *et al.* (1998), Chang and Yang (2001) and Yang *et al.* (2001). They have utilized FVM into their simulation by using the Navier-Stokes equations in the numerical methodology in the flow field calculation.

Chang *et al.* (1998) analyzed on the dynamics of air trap in the encapsulation process of microelectronic package by both experiments and simulation. They developed a computer-aided engineering (CAE) to study the coupling non-Newtonian fluid flow, heat transfer and chemical reaction involved in the moulding process. They found that in the case of air trap is caused by the unbalanced lead-lag flow pattern on the top and bottom mould halves. They also suggested some modification to the product and the results are verified by the experimental result conducted in moulding trials.

Yang *et al.* (2001) analyzed the mould filling process as the non-isothermal, compressible and suitable for both Newtonian and non-Newtonian fluids. Major improvement had been notified over the previous work such as incorporation of the time dependence of the fluid and structural behaviour and the incorporation of the two phase flow effects which also believed to a complete description of all phenomena that has important effect in wire sweep.

Chang *et al.* (2004) and Yang *et al.* (2006) viewed that FVM is more efficient and robustness. It is utilized to solve 3-D governing equations of flow and heat transfer. Their approach also combines the efficiency of Semi-Implicit Pressure-Linked Equations (SIMPLE) and the robustness of the volume-tracking method (VOF) to solve the coupled two-phase model in order to simulate the transient, non-isothermal and non-Newtonian in the fluid flow of the moulding process. The SIMPLE is an iterative decoupled procedure for coupling velocity and pressure, in which the three linearized momentum equations are solved for a guessed pressure field, sequentially followed by solution of the pressure correction equation. Chang *et al.* (2004) carried out the comparison between the experiment and simulation of melt front location with various time steps and formation of the air trap whereas Yang *et al.* (2006) manipulated the resin melt flow that will exert drag force on wires to predict the wires deformation.

Pei and Hwang (2005) have studied on three-dimensional paddle shift modelling for TSOP. Their methodology is based on modelling of the flow of the polymer melt around the leadframe and paddle during the filling process, and extracting the pressure loading induced by the flow on the paddle. The SIMPLE method with a FVM discretization and the volume of fluid (VOF) of two phase treatment is used in the mould filling process. Pei and Hwang (2005) also extended the analysis to the wire sweep prediction with the effect of wire density.

Since the S-CSP is a new and complicated technology, literature reviews on mould filling process of the package is extremely limited. One of the earliest simulations of the S-CSP was conducted by (Lee *et al.*, 2006). They have analyzed three die stacking of 4 x 4 mould arrays with four different gates. They found that the severe void problem was one of the challenging factors to determine the manufacturability. The investigation was not limited to the void problem but also on flow retardation phenomena, shear stress, and wire sweep in the package.

2.4 Front tracking method

An important and challenging application of computational fluid dynamic (CFD) are interfacial and multiphase flows that involved multiple immiscible fluids separated by one or more interfaces. These flows occur in many natural and industrial processes. In a three-dimensional (3-D) filling simulation, accurate tracking of the melt fronts (or polymer-air interface) as well as the representation and evolution of their complex topology are very important. Various techniques for the interface tracking have been solved using the marker-and-cell (MAC), the flow-analysis-network (FAN), the VOF, and the pseudo-concentration methods are incorporated in volume tracking method which based on fixed mesh.

In the VOF method (Hirt and Nichols, 1981) and the pseudo-concentration method (Liang *et al.*, 2005), the melt front can be tracked by solving the transport equation of the fractional volume function. The transport equation can be solved by either in the geometrical approach or the algebraic approach (Chang and Yang, 2001). In the geometrical approach, the computational domain only includes the filled region. At every time step, the interface needs to be reconstructed in order to calculate the fluid fluxes across the cell faces and to impose the boundary condition on the melt fronts in each partially filled cell. In the algebraic approach, the computational domain consists of both the filled and empty (air) regions in the cavities, and it is not necessary to impose the boundary conditions on melt fronts. The melt fronts are tracked directly by solving the VOF transport equation of the fractional volume function. For the pseudo-concentration method, it is a variation of the original VOF method. The pseudo-concentration function, F is defined either it is equal to one for fluid region or equal to zero for empty region whereas the continuous function F has value in between one and zero at the melt front.

Haagh and Vosse (1998) have adopted the pseudo-concentration method to develop the 2-D and 3-D mould filling simulation. They employed pseudo-concentration method which is related to the volume-of-fluid (VOF) method. Gethin and Abdullah (1997) applied the pseudo-concentration method to model the free surface that separates the fluid region from the empty region.

As noted by Louma and Voller (2000) and Yang *et al.* (2001), the melt front during polymer mould filling can be tracked using the VOF equation. The VOF scheme is able to compute in a fully automatic manner flows where liquid masses coalesce, disintegrate or undergo other arbitrary geometric or topologic transformations (Yang *et al.*, 2001). Han *et al.* (2000) applied a control volume method with a fixed finite element mesh to predict the fluid front advancement. The fluid front is determined by a surface passing through the nodes with partially filled control volume cell ($0<f<1$). Han *et al.* (2002) still use the same method in their extended studies.

Chang *et al.* (2004) utilized a volume fractional function *F* for tracking the advancement of melt front in the moulding process. The no-slip boundary condition was applied at the mould walls whereas for the hyperbolic volume fraction advection equation was set at the inlet boundary condition. Pei and Hwang (2005) reported that their software also used the VOF method for solving the two phase flow. Liang *et al.* (2005) and Kulkarni *et al.* (2006) have explained that front tracking is needed to model the flow of fluid during the filling phase. Their front tracking algorithm that based on pseudo-concentration function gives a smooth representation of the free surface. They added an artificial diffusion term in pseudo-concentration algorithm to allow partial slip at the fluid wall interface and to damp numerical oscillation as proposed by Ashgriz and Poo (1991).

Zhao *et al.* (2005) used the control volume method to trace the position of the flow fronts after the flow analysis network (FAN) using two typical 3-D control volumes; an internal node and a boundary node. However, they found that the 3-D control volume is more complicated.

2.5 Summary

A numerous effort has been done by both experiment and simulation of moulding process. Previously, most of the researchers studied the fluid flow using FEM that based on Hele-Shaw approximation. However, due to the time constraint and large memory required made it has no practical use in a challenging and rapid development rate of new technology in the electronic industry. Since then, researchers tried to look for an appropriate method. Alternatively, they shifted into finite volume method (FVM). The FVM is easier, has less computing time and memory application can be manipulated to investigate the fluid flow phenomena in the mould filling process. The non-Newtonian behaviour of the moulding compound has been modelled either by Cross or Castro-Macosko models. All researchers have used Volume-of-Fluid (VOF) technique to track the melt front during mould filling process. The method is easy and simple to use which made it to be the most popular technique. By these reasons, most of the researchers and commercial codes (Moldflow®, Moldex-RIM®, etc) use VOF technique for tracking the melt front in their mould filling simulations. Tables 2.2 and 2.3 show the literature of numerical models between 2-D and 3-D models applied in mould filling simulation.