Encapsulation Process Study and Yield Model for Smart Phone Manufacturing

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Abstract. The demand for microelectronic manufacturing grow dramatically. Products with handheld applications are rapidly moving towards miniaturization and higher performance. This trend has accelerated the need for continuous miniaturization within the integrated circuit (IC) packaging industry. The solder balls located on the bottom side of component offers electrical connection. During service environment, the mismatch of Coefficient of Thermal Expansion (CTE) may result in fatigue failure of the solder interconnection. The encapsulation using underfill process helps protect solder balls from damage. In the telecommunication industry, metal shielding is used to cover the electronics component to reduce the influence of electromagnetic wave. This further complicates the underfill process. This study focuses on the BGA (Ball Grid Array) memory and CPU (Center Process Unit) device. Firstly, the cause-effect diagram is used to explore key factors on the occurrence of voiding, incomplete underfilling and overflow. Taguchi experimental design is then employed for process optimization. Secondly, the underfilling of encapsulant should complete before the occurrence of material gelling. Thus, the material characteristics at the optimal process scenario are investigated through the flow experiments. Finally, the Monte Carlo analysis is conducted to sample data of certain distribution, and predicted the flow time required for components of specific dimensions as well as the gelling time. The process yield of encapsulation can therefore be determined.

Keywords: Microelectronics manufacturing, Encapsulation, Underfill, Taguchi experimental design, Monte Carlo Simulation

1. INTRODUCTION

Amid increasingly shrinking electronic product design the semiconductor package technology is poised with high density of break over points, limited spacing and large quantity in meeting the rising demands of high performance. Assessing electronic package reliability is critical to the electronic packaging industry. The strength of the solder ball for electric connection is key to product quality. Solder balls at the bottom of electronic components connect the latter and PCB or transmits signal. Components made of different materials may have their own Coefficient of Thermal Expansion (CTE) and may end up with poor soldering points. The latter are poised to result in hot fatigue and components damage due to lost or broken connection points due to displacement. Manufacturers also suffer with poor process yields and reliability in the future.

Filling the bottom side (underfilling) with gel in the packaging process was first adopted in C4 (Controlled Collapse Chip Connection) technology developed by IBM in 1960 to reduce hot stress suffered by solder balls and components. This mechanism connects the chips and high-temperature resistant sub-strates with bumps, assemble them with Surface Mount Technology (SMT), fill the gap between chip and PCB with package material by capillary force, and improve on the components soldering strength and fatigue resistance of solder balls. This technique is adopted for Chip-Scale Package (CSP) components soldering to improve on the reliability required by handheld devices as well as cut the failure rate due to long term exposure to high temperature, high humidity and heavy shock and prevent the leakage flow of leak the current transmitted by foreign matters contained in the solder ball and extend the fatigue life of the contact point by curbing solder ball breakage. All these are attracting more and more attention from middle and high end mobile phone manufacturers on Underfill Technology.

This technology comes with its own shortcomings as indicated by M M. Yazdan (2016) including bubbles, under and over gel fill. LAI Chengzhan (2003) argues that the longer time required by underfill may lengthen the operating time, cut production performance, generate more bubbles by its capillary flow or partial fill due to weak capillary force. Manzione *et al* (1990) noted that pressure settings in the plastic injection process may leave bubbles or only partially fill the space after packaging and proposed a method for an optimum pressure setup. QIAN Zhenhuan (2006) noted that injecting liquid polymer gel to one side of or in-between flip-chip dice may drive accumulated gel into the space between the dice and PCB. This may lead to bubbles or only partial filling in case of poor gel flow force. These contribute to low yield and reliability. Tackling this problem mandates an optimized underfill process parameter and the creation of relevant models.

Delmdahl (2016) and Li (2016) suggest that scores of factors may result in poor component functions or uneven features.

Smartphone manufacturers add a metal shielding to the SMT process to curb electromagnetic waves brought by mobile phones. This leads to a limited jet injection points and more demanding control to prevent over-gel in a later underfill process. The tolerance enjoyed by metal shield and components also contribute to these flaws. As only very limited researches are available now, this study is trying to review, optimize , and flow modeling the underfill process for key components of smartphones including the Central Processing Unit (CPU) and memory.

2. Research Purpose

This paper is aimed at dealing with bubbles, under and over gel filling in the underfill process due to long filling time or weak capillary force with goals outlined below:

1. Explore key factors of impact on bubble, under and over gel fill before optimizing the process parameter of target products with the Taguchi experimental design for better yields.
2. Build a flow velocity model to identify flow characteristics of materials under different temperature conditions, predict underfill time and its variances among electronic components of different dimensions and gelling time and its variances.
3. Predict yields with the Monte Carlo simulation methods by taking the PCB temperature, gel characteristics (stickiness) and product characteristics (including components dimension and spacing from PCB) as well as recommend pre-heating temperature of PCB of new products.

3.1 Taguchi quality engineering

Kemal Subulan and Mehmet Cakmakci (2012) suggest that the Taguchi experiment design not only enables systems or technique optimization in product development or process improvement but also cuts costs and time for the feasibility study. This paper reviews and selects process parameters with a cause effect chart before designing an experiment plan and orthogonal array setup and run data analysis (SN ratio and variance analysis). The optimized parameter mix will then be used by a flow velocity model for the experimental parameter range setup.

3.2 Flow velocity model

Scores of factors may create an impact on the flow of underfill gel including material characteristics, components dimension, conditions of sub-strate surface, and gel injection pattern. See Formula 1 for the relationship between the leading edge speed of the capillary flow and the contact angle between the upper and the lower flow surfaces, gap height, gel surface tension and viscosity (Fosberry, 1996).

$$v_{front} = \frac{\Upsilon h(\cos\theta_1 + \cos\theta_2)}{12\eta X} \quad (1)$$

Where v_{front} is the flow velocity of the gel at its leading edge, γ the surface tension, h the gap height, θ_1 and θ_2 the contact angle between upper and lower flow surfaces, η the gel viscosity, and X the flow distance.

3.2.1. Temperature function model

This is aimed at identifying the function of individual experiment combinations and reviews its temperature and time relations. Take the natural log of slope (Arrhenius) to get a linear relation with temperature reciprocal as shown in Formula 2 (Huang, 1996). Different board temperatures may lead to different slops which may be used in comparing flow velocity and determining the time needed to flow through given the speed on account of experimental results. That is the impact of temperature on flow velocity.

$$\ln S = \ln \frac{X^2}{t_0} = a + b \left(\frac{1}{T}\right)$$

(2)

where S is the slope of distance over time, X the flow distance, t_0 the time to fill gel for a distance of X, T the absolute temperature, a and b the constant after regression.

3.2.2. Modify wettability

The flow velocity experiment run by this paper employs a slide as the flow surface of gel which differs from the one of PCB and components in a practical process. This leads to different wettability of the underfill gel. Formula 3 is used to modify flow velocity of the gel under wettability of actual production (Huang, 2000)

$$t_{flow} = t_0 \frac{2\cos\theta_g}{\cos\theta_p + \cos\theta_c} \quad (3)$$

Where t_{flow} is the time required for the gel to make complete filling, t_0 the time to fill the gel for a distance of X, θ_g the contact angle with the slide, θ_p the contact angle with PCB, θ_c the contact angle with component surface.

3.3 Process yield prediction by the Monte Carlo method

Babiker (2016) suggests that the results of simulation by the Monte Carlo method may be aligned with ideal equipment. This benefits a lot as it's easy to compare different scenarios:

Save costs and time taken by direct experiment, observation and study over system changes.

Identify regular changes of the system with repeated simulation.

Show insight into problem solution when other management science methods fail, predict performance of the current system under modified conditions without interruption to its existing operations and identify hidden flaws and issues in the actual production environment. In many case, the highly competitive and costly electronic industries just cannot afford to shut down the production line for an experiment. Simulation is the only way to predict production yield and improve the process without the forbidden costs and time suffered by its conventional counterpart.

3.3.1. The Monte Carlo simulation theory

The Monte Carlo simulation method is used in solving problems with probabilistic interpretation where each impact factor can be presented with a probability rather than specific mathematic formula to get an approximate solution. The probability distribution of each random variable has to be determined before applying this method. A random sample of this variable is then set with a random number and finds a solution with the data acquired. It is employed to get an approximate value in risk analysis including financial accounting, reliability estimates and cases where a physical experiment is just impossible to do. This method enjoys the following advantages:

It's easy to estimate results and compare variances among them if a simulation model is available.

Save costs and time taken by a direct experiment, observation and study over system changes.

When predicting production yield with simulation technology in the highly competitive and costly electronic industries saves a lot in components consumption and production line down time. This paper will simulate the gelling probability with the Monte Carlo simulation by software package Crystal Ball. A case study is conducted with BGA components (CPU: 14mm x 14mm x1mm and Memory: 13mm x 11.5mm x 0.96mm) adopted by the mobile phone manufacturer.

3.3.2. Generation of random variables

The Monte Carlo simulation mandates random sampling, *i.e.* every sampling value is subjected to its own probability distribution. A random variable enjoys the same probability of being samples every time regardless of the results of earlier sampling. Let *F(X)* the cumulative distribution function of variable X, the probability of $X <$ any real number "a" is shown in Formula 4:

$$F(a) = P\{X \le a\} = \int_{-\infty}^{a} f(x)dX \quad (4)$$

Probability of X in between two real numbers a and b, $a < X < b$, is shown in Formula 5:

$$v_{front} = \frac{\gamma h(cos\theta_1 + cos\theta_2)}{12\eta X} \quad (5)$$

The cumulative density function of any real number “a” is characterized by Formula 6 and 7:

$$\lim_{a\to\infty} F(a) = \lim_{a\to\infty} \int_a^{\infty} f(x)dx = 1 \quad (6)$$

$$\lim_{a\to-\infty} F(a) = \lim_{a\to-\infty} \int_{-\infty}^{a} f(x)dx = 0 \quad (7)$$

Random variable $F(x)$ is the uniform distribution in interval (0,1). Let $F(x)$ equal to uniform random number r after the latter was generated.

Identifying distribution of the population for sampling. As variance of all variables under consideration of this paper are subject to the impact of random variables x1,……, xn the Central Limit Theorem tells that their variances will be in a normal distribution when enough number of samples are drawn from the population. In a normal distribution the more a value is close to the mean the higher probability that it may occur.

Monte Carlo simulation sampling requires a large enough number of samples to get the function distribution close to the real situation and numeric characteristics. To get more precise simulation and cut sample variances to the actual level of mass production, it is necessary to increase the number of samples drawn. With an insufficient number of simulations, the placement yield prediction may suffer great variance (the so called labile status). This is not the case with a sufficient number of simulations as the simulation results get stable and the placement yield prediction gets closer to the actual production environment. This study runs the simulation for ten thousand times to get more realistic production status.

The random sampling employed by the Monte Carlo simulation in this paper is conducted in the steps described below:

Step 1: get one set of samples in a normal distribution at a given flow time average and standard deviation.

Step 2: get one set of samples in normal distribution at a given gelling time average and standard deviation.

Step 3: compare flow velocity and gelling time one by one

(a) Set a sample record as normal if its flow velocity time is greater than its gelling time

(b) In case the flow velocity time is less than gelling time then calculate its ratio to get yield after the underfill has gelled.

This study assumes the variance of a given flow velocity time in normal distribution with average at μ and variance at σ2. Select a random constant in range of 0~999, say 751, then its random normal variable 0.7 can be derived from the standard normal cumulative probability chart. The formula “flow velocity average + random normal variable x flow velocity time standard deviation = flow velocity time” then gives the flow velocity time and gelling time of this sample and the ratio of the two may be set as the yield.

4. Method

This study tries to optimize the gel injection process for active components CPU and memory of phone Model A which features a metal cover capped PCB for electromagnetic wave shielding. The metal cover is bored for gel injection at points #1~#6. A marker point (#7) is added on the PCB to for the gel injection completion identification which prevents confusion in the production line as shown in Figure 4.3. The gel injection holes in the metal cover are located beside individual components which enables the injected gel to fill the gap in between chips and PCB by capillary forces. See Figure 1 for metal cover removed PCB for relative positions of the gel injection holes and components.

CPU and memory used in this study features the ball grid array (BGA) package. The CPU is of dimension 14mm x 14mm x 1mm (LxWxH) with 533 solder balls hollow arrayed beneath the PCB while the memory 13mm x 11.5mm x 0.96mm (LxWxH) with 153 solder balls beneath the PCB. CPU and PCB is 0.17mm-0.18mm spaced apart while memory and PCB 0.14mm~0.16mm.

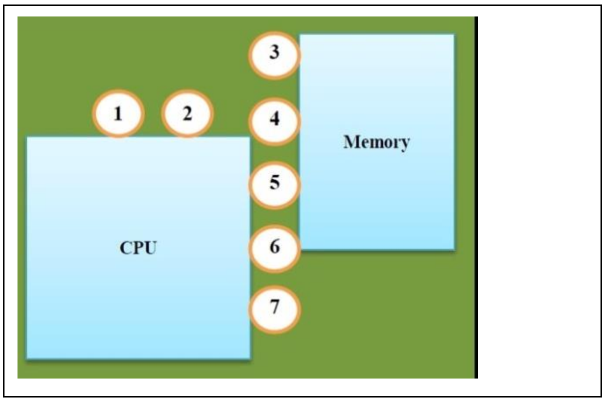


Figure 1: Relative positions of gel injection holes and components

The H-brand underfill gel is composed of ingredients including epoxy resin, hardener, catalyst, filler and other additives. The catalyst may have an impact on the temperature and tackiness of the crosslinking reaction in gel (Shijian, 2000). As recommended by the gel supplier, gels are subject to warming up for 4 hours before their use (open up bottles storing them) to prevent condensing due to exposure to external environment and changing tackiness. Bottled gel may be kept for 6 month in a refrigerator at temperature -20 ±3℃ and 5 days at room temperature after unfreezing. It features a viscosity of 6,000psi at temperature of 25°C with glass transition temperature (T_g) at 115°C.

4.1 Process parameter and level

Scores of flaws may be found in the gel injection process including bubbles, under and over gel fill on account of PCB quality, components design, gel characteristics, injection machine settings, and process conditions. Bubbles may be a result of irregular leading flow, impact of solder balls, gel blocked by flux residual, dirt on PCB surface, PCB temperature control, warped board, temperature of gel injection nozzle, aged gel, inter-actions by gel injection orders and positions, and pushes between adjacent gel injection points. Gel aging, frequency of gel warming and unfreezing, and applicability of gel in room temperature are correlated with the gel aging speed. Under gel fill may be caused by blocked gel flow by flux residual, insufficient gel injection, and gelation before gel fill. Over gel fill may be contributed by over injection, improper interval between two consecutive injections, too small gap between metal cover and components, component form factors (including its dimension, gap between components and PCB, and solder ball array), too close a gel injection tip to the PCB.

This study runs experiment over the factor of gel injection quantity, time span between consecutive gel injection points, gel injection orders and board temperature to determine the optimum process parameter mix. See Table 1 and description below for parameter level setup.

1. Total gel injection quantity: take gel injection quantity and gel injection position from current production (74mg) and set ±10% of it as experiment level (67mg, 74mg, 81mg) to determine the optimum total gel injection quantity on account of gel costs and product reliability.
2. Time span between consecutive gel injection points: the production line of this study employs a panel carrying 8 PCBs. The first gel injection machine takes care of the first four PCBs while the second the later four of them. Each machine takes 23 seconds to inject the gel. Upper limit of time span between consecutive gel injection points is 23 seconds less total time from one PCB to the next (4 PCBs require 3 moves with each move lasting 2 seconds) which is 6 seconds. There are 17 seconds left to 6 gel injection points on 4 PCBs (a total of 24 points). This leads to a maximum waiting time of 0.7 seconds and the selection level is thus set to 0.01, 0.35, and 0.7 seconds.
3. Gel injection orders: GAN Lixing (1999) found that the change gel injection path may cut filling time, *e.g.* extend gel injection points along both sides of the components. In addition, the flow of the gel may get faster when nearing the wetted solder ball and get slower after being reached and started wrapping the ball. This study takes the gel injection position, relative position of target component to be gel filled and solder ball density in the filling area into account and experiment with three gel injection path levels of pattern “T” (T-123456) and “I” (I-34567, I-54637).
4. Board temperature: Flow of gel in gel injection process may get better by pre-warming the PCB as viscosity of the gel may decline and free more easily. The flow speed gets slower and becomes solid along with gelation. This study sets the warm-up temperature at 70℃, 85℃ and 100℃ as suggested by technical data sheet (TDS) of the gel material employed.

This paper employs an L_9 orthogonal array of the Taguchi experiment with 4 levels and 3 factors for 2 experiment runs. The response variable is set to a ratio of the gel filling area (the gel filling area beneath components divided by the components area) which is closer to 100% the better. The LTB data analysis of this study employs the following criteria. Regarding bubbles: Solder balls at the outer four rows cannot have more than two consecutive ones wrapped in bubbles. Bubbles in the center of components (without solder ball) cannot account for more than 35% of the components area. Regarding the coverage area: Underfill gels shall cover at least 90% of the components area with solder balls at four corners completely covered. Regarding over filling: Area of components covered by gel cannot account for 20% of the total and exceed more than 3mm over edge of metal cover.

An experiment is designed to determine the gel injection nozzle temperature and flowrate to cut variance in gel injection quantity. With the target gel quantity set to 6mg, the experiment runs 32 times with gel injection quantity set at 0.15mg/dot, 0.30mg/dot, 0.45mg/dot and temperature at 50℃, 60℃, 70℃. Gel injection quality under these nine sets of conditions (nozzle temperature and gel injection rate) is measured along with the process capability index (Cpk) analysis. Outcome of these experiments suggest the best Cpk of the gel injection rate of 0.30mg/dot and nozzle temperature at 60℃. These two set the fixed parameter in later experiment design.

The ProgRes2.7.7 microscope software is used in calculating the filling area by steps below: Identify area of flaws including bubbles and under fill, calculate area ratio of each experiment conditions, determine qualification of samples under individual experiment construction. The experiment outcome suggest sample 4-1 (the fourth experiment run with the first duplicated sample comes with a coverage rate of 95.5% and with bubbles), 7-1 (with coverage rate of 99.3% and with bubbles), 9-1 (with a coverage rate of 91.11% and with bubbles), 1-2 (with a coverage rate of 95.18% and with bubbles), and 2-2 (with a coverage rate of 99.22% and with bubbles). These experiments indicate major flaws of under fill and bubbles.

The SN ratio of total gel injection quantity of 67mgs and 74mgs outperforms that of 81mg, *i.e.* more gel supply does not help in raising the filling area. The 0.35 seconds interval is better than the 0.01 and 0.77 seconds ones, *i.e.* more time in the range of 0.01 and 0.35 seconds enables gels of the next gel injection point to fill the area (missed) filling in the last point while adding more time after 0.77 seconds may lead to more bubbles due to irregular leading edge of gel flow. The best gel injection path is I-54637 which prioritizes the gel supply to gel injection points along both sides of the components (hole ID 4, 5, 6 and relative to the worst route of I34567) as it leads to a more uniform leading edge of flow which results in less bubble generation. The T-pattern gel injection employed by this study is the I-pattern for memory components with less gel supply and leads to under fill due to insufficient gel supply. The T-pattern for CPU is an L-pattern which may lead to bubbles along the diagonal of gel injection route. Sample of board temperature at 85℃ is better than 70℃ and 100℃ as gel viscosity rises along with the temperature. Gel at a temperature below 70℃ may flow too slowly and generate bubbles yet a too high temperature may also lead to early gelling which results in bubbles or under fill.

4.2 Flow velocity model and yield prediction

The flow velocity experiment at this stage is aimed at simulating variance of gel flow velocity at different temperature conditions with a gap between the real components and PCB at 0.16mm as well as the relationship between gel flow temperature (board temperature) and gelling time point. The Monte Carlo simulation is then used to isolate impact factors of flaw "under fill" (gelation before the gap is filled up) into average and variance for simulation input protection. The Crystal Ball risk analysis software is used to determine the probability of the flow being less than or equal to tgel (*i.e.* yield of underfilling process) as well as ideal board temperature settings with given components size and defect rate.

Flow velocity model

Design and execute experiment on flow velocity of gel in between the slides to determine time function of gel flowing through chips of different sizes under different temperatures. This is aimed at effectively simulating flow characteristics of gel in actual products by correcting flow velocity with measurement of gel in different surface wettability (contact angle) by taking the variance of flow characteristics of gel on experiment slides against the substance of components/PCB surface.

Flow velocity experiment

This experiment is aimed at identifying flow characteristics of gel at temperature 75℃, 85℃, 95℃ (10℃ below and above the best board temperature (85℃) determined earlier). Slides are employed as the flow surface for easy visual observing relationships between flow distance and time. Slides are 0.16mm spaced apart with 0.16mm steel blocks inserted and fixed in between. Placing a specimen atop the metal block and warming it up with a heater. Apply H brand thermal grease between the specimen and metal block for effective and uniform heating. Inject gel with syringes (of capacity 3ml, dimension 0.55 mm x 25 mm, and needle of diameter 1.25mm) after the sample is heated to the desired temperature (around 5 minutes). Supply gel throughout the experiment for 20 minutes. Run this four times at different temperature conditions.

Time required for fill up

The model is designed to determine the relationship between the square of the gel flow distance and time. Take a natural log of the curve (slop) and its linear with temperature reciprocal according to the Arrhenius Theorem. This flow represents a flow velocity at different board temperature while the model gives time to flow through a given distance. The flow velocity of gel at a board temperature of 95℃ and 85℃ is much faster than at 75℃ for the first three minutes. For ModelA product at current board temperature 75℃-85℃ for the production of phone ModelA. Automatically, it takes about 40 seconds to fill the bottom of the components of length 14mm (area 256 mm2). Figure 5.3, 5.4 and 5.5 illustrates the relationship between the square of the gel flow length and time. The experiments indicate that there is a linear relation between gel flow length and time before gelation. With board temperature at 75℃, 85℃, 95℃ the slop of it is 6.42, 7.43 and 10.95 respectively. This linearity breaks and variance in the flow velocity rises sharply. Goodness of fit of this linear relation is worse than R-sq=99.0% in this experiment while the average gelation time span at different temperature conditions (75℃, 85℃, 95℃) are 175, 125, and 77.5 seconds, respectively. At a lower board temperature, gelation takes a longer time to happen and less time at a higher board temperature. Distance of the gel flow before gelation at a higher temperature is shorter than the lower temperature ones. In addition, bubbles and un-uniform leading edge of the gel flow are found in every temperature condition (*e*.g. 85℃). Board temperature is critical in getting at the space below the components are filled up completely before gelation.

Take the first sample. Gelation occurs in 170, 130, and 60 seconds at temperatures 75℃, 85℃, 95℃, respectively. Values of natural log over the ratio ($S = X^2/t_0$) of the individual square of the distance traveled in this time span over time (ln*S*) are 1.859, 2.004, 2.391 while the reciprocal of the absolute temperature (1/T) is 0.002849, 0.00277 and 0.002695. The relationship between ln*S* and 1/T by regression analysis is shown in formula 8 (with goodness of fit at 84.9%). Function of time (t_0) required for gel to fill up the space of length *X* is shown in Formula 9.

$$\ln S = \ln\frac{X^2}{t_0} = 11.63 - 3443\left(\frac{1}{T}\right) \tag{8}$$

$$t_0 = \exp(\,2\ln X - 11.63 + 3443\left(\frac{1}{T}\right) \tag{9}$$

Adjust impact of surface wettability on gel flowing

This flow velocity experiment takes a slide for the gel flow surface which differs from the substance of components and PCB surface in the actual production process. The relationship between the leading speed of the capillary flow, contact angle and gap height between the upper and lower surfaces, and surface tension and viscosity of the gel during gel filling operation is shown in Formula 3.7 (Fosberry, 1996). This experiment is aimed at finding the variance of the gel in a different surface, wet to adjust prediction by flow velocity experiment. Warm up components, PCB and slide to 80℃, inject one drop of gel to these surfaces with a syringe and measure the contact angle of the gel to each surface 20 seconds later. Angles to surfaces of the slide, PCB, and components are 25°, 28° and 31°, respectively. With selected gel brands, viscosity (γ) and surface tension (η) remain constant, the gel-slide surface angle at 25° and components-PCB gap at 0.16mm, the gel flow velocity on the slide surface is defined in Formula 5.3. As the leading speed of the gel is proportional to the sum of the cosine of the upper/lower surface contact angle (Formula 10) the adjusted time (t_{flow}) required to fill up the gap between components and PCB surface may be revised as shown in Formula 11.

$$v_{front\text{-}glass} = \frac{\gamma\times 0.16(\cos(25°)+\cos(25°))}{12\eta X} = \frac{0.289\gamma}{12\eta X} \tag{10}$$

$$t_{flow} = t_0\frac{2\cos\theta_g}{\cos\theta_p+\cos\theta_c} = \exp(2\ln X - 11.63 + 3443\frac{1}{T}\times 1.04) \tag{11}$$

Variance of fillup time and gelation occur time

Repeat the experiment in individual temperature conditions. The fillup time at board temperature 75℃, 85℃, 95℃ is 39.81 seconds, 34.54 seconds and 23.47 seconds, respectively, and average gelation time of 165(s), 127.5(s) and 90(s). That is, the higher the board temperature is the shorter the fillup time is, the earlier gelation time is, and the greater the variance is. Warmer board may shorten the process time at the expense of more “under fillup” flaws due to early gelation and greater variance.

Monte Carlo process yield prediction

Determine averages and variances of fillup time and gelation occur time at different temperature conditions with figures from these flow velocity experiment and predict the yield of successful components fillup under different temperature conditions with the Monte Carlo simulation method.

This study predicts the production yield with simulation methods to reduce the time and costs at the process development stage. Determine board temperature settings against products of the components at a given dimension. This study assumes a normal distribution of time (t_{flow}) required for completely filling up the components area and gelation occur time (t_{gel}) as shown in Formula 12 and 13 Flow velocity data out of the experiment under different temperature connection are used to determine the average and standard deviation of time required for complete filling up components area and gelation occur time as input parameter for process yield prediction by Monte Carlo simulation.

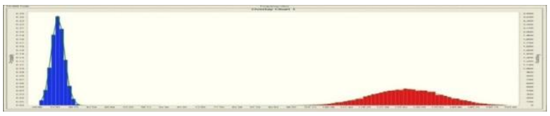
$$t_{flow}=N\left(\frac{X^2}{S},\sigma_{flow}\right) \quad (12)$$

$$t_{gel}=N\left(\exp\left(\left(2\ln X-11.63+3443\frac{1}{T}\right)\times 1.04\right),\sigma_{gel}\right) \quad (13)$$

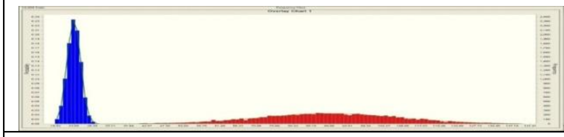
where σ_{gel} and σ_{flow} are standard deviation of time required for complete filling up components area and gelation occur time

Random sample 10,000 times of the time required for completely the filling up components area and gelation occur time at these three temperature conditions with the Crysball software. Under different temperature conditions if, if tflow is greater than tgel then set the filling as acceptable one and rejectable one vice versa. Distribution of simulation sampling time required for complete filling up the components area and gelation occur time at individual temperature conditions as illustrated in Figure 2. Overlapped area indicates the probability of gelation before complete fillup (*i.e.* risk area) and the high temperature conditions account for a larger area. Outcome of the simulation suggests that a 100% process yield may be reached at board temperature 75℃ and 85℃ but was not the case at temperature 95℃. Yield of the latter down to 99.98% as a result of 200ppm fraction defective. In this case, board temperature at 85℃ is recommended on account of the output requirements and risks of poorer quality.

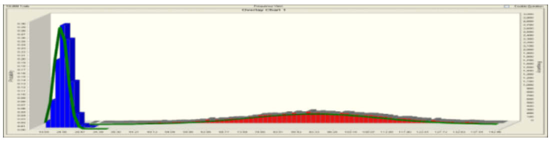
Distribution of simulation sampling of time required for complete filling up components area (blue) and gelation occur time (red) at 75℃



Distribution of simulation sampling of time required for complete filling up components area (blue) and gelation occur time (red) at 85℃



Distribution of simulation sampling of time required for complete filling up components area (blue) and gelation occur time (red) at 95℃



Distribution of simulation sampling of time required for complete filling up components area (blue) and gelation occur time (red) at 95℃

Figure 2: Distribution of simulation sampling of time required for completely filling up the components area and gelation occur time.

5. CONCLUSIONS

The underfilling technique is getting more important as signal transmission solder points in electronic products tend to break due to thermal fatigue by the heat cycle generated in its use. Metal shielding metal caps are complicating this technique as it imposes more restrictions on gel injection point availability and more demanding control on gel quantity applied at individual components. This study reviews the impacts of process flaws of bubbles, under fill and over fill as well as design and execute an experiment for process parameter optimization against individual products. The preliminary experiment finds the best gel injection nozzle temperature and injection rate at 60℃ and 0.30mg/dot in terms of process capacity (variance level) of the injection rate. The process optimization experiment suggests the optimum parameter mix of the total gel injection quantity at 74mgs, time span at 0.35 seconds, injection route at I-54637 and board temperature at 85℃.

Run gel flow velocity experiment at temperature minus and plus 10℃ of the best board temperature (85℃) to observe the flow characteristics of the gel on the slide at different temperature conditions. Another experiment followed for wettability of the surface where gels flow on and flow velocity correction to simulate flow characteristics of gel between chip and PCB and get gelation time at different temperature conditions. Both experiments suggest the square of the flow distance before the gel gets solidified is linear to the time. As the board temperatures of 75℃, 85℃, 95℃ slope of curve is 6.42, 7.43 and 10.95, and fillup time is 39.81 seconds, 34.54 seconds and 23.47 seconds, respectively, we can conclude that the injected gel flows faster under higher board temperatures. Average gelation time is 175 seconds, 125 seconds, 77.5 seconds, respectively which suggests raised board temperature may shorten the process time at the expense of more "under fillup" flaws due to early gelation and shorter flow distance. The Monte Carlo simulation method is then used in estimating the fillup and gelation time for (different sizes of chips) at different temperature conditions for the prediction of the underfilling process yield. Outcome of simulation suggests 100% process yield may be reached at board temperature 75℃ and 85℃ but was not the case with temperature 95℃. Yield of the latter down to 99.98% as a result of 200ppm fraction defective. In this case, board temperature at 85℃ is recommended on account of output requirements and risks of poorer quality.

Addressing the underfilling process parameter optimization, the flow velocity modeling and yield prediction this study may have the following contributions to the industry:

1. In spite of scores papers on underfill only a few were made on handheld electronic products (gel injection through limited holes in metal caps for electromagnetic wave prevention). Outcomes of this study may of help in the new process development.
2. The preliminary experiment on the control factor of gel injection nozzle temperature gives 9 variances of gel injection quantity at different temperatures. Enterprises may rely on this for gel injection quantity control.
3. The best parameter mix determined by the Taguchi method may provide general assessment on new product process.
4. Simulating the gel flow velocity with s slide to get gel flow characteristics under different temperature conditions may cut the costs of pilot runs by adjusting the process before gel injection operations.
5. The function of time required for fillup with regression analysis in the gel flow velocity experiment provides fillup time and speed of components with different dimensions at different temperature help in improving precise capacity prediction.
6. Simulate flow distance at different temperature to estimate gelation time of components of different dimension with the Monte Carlo simulation to help predicting new product or process yields with minimized materials and costs.

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