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Modeling and Control of Time-pressure Dispensing for Semiconductor Manufacturing

Cong-Ping Chen[1,*] Han-Xiong Li[1,2] Han Ding[2]

[1] School of Mechanical Engineering, Huazhong University of Science & Technology, Wuhan 430074, PRC
[2] Department of Manufacturing Engineering and Engineering Management, City University of Hong Kong, Hong Kong 999077, PRC

Abstract: To improve the consistency of the adhesive amount dispensed by the time-pressure dispenser for semiconductor manufacturing, a non-Newtonian fluid flow rate model is developed to represent and estimate the adhesive amount dispensed in each cycle. Taking account of gas compressibility, an intelligent model-based control strategy is proposed to compensate the deviation of adhesive amount dispensed from the desired one. Both simulations and experiments show that the dispensing consistency is greatly improved by using the model-based control strategy developed in this paper.

Keywords: Time-pressure dispensing, consistency, fluid flow rate model, model-based control.

1 Introduction

Automatic fluid dispensing has been widely used in semiconductor manufacturing and circuit assembly, such as the development of the advanced integrated circuit encapsulation (AICE) and surface mount technology (SMT)[1,2]. In all these applications, four kinds of dispensing methods are often employed. They are time-pressure dispensing, argue pump dispensing, true positive displacement dispensing and jet dispensing. Among these dispensing methods, time-pressure dispensing is the most widely used dispensing technology due to its low cost, simple operation, ease of maintenance and flexibility for different applications. It is estimated that about 70% of the dispensing machines or systems currently use the time-pressure approach[3].

Fig. 1 shows the schematic of a typical time–pressure dispensing system. When the valve is opened, the pressurized air flows through a transmission line to the syringe to squeeze the fluid out to a wafer or a substrate. The fluid amount dispensed is affected by many factors, such as dispensing pressure, dispensing time, temperature, fluid flow rate, compressibility of the gas, *etc.* Among them, the fluid dynamics is one of the most significant influences on the dispensing consistency.

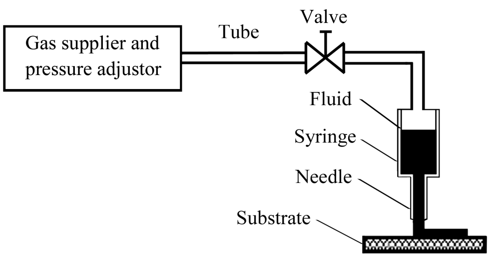

Fig. 1 Simple scheme of a time-pressure fluid dispensing system

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*Corresponding author. E-mail address: mechencp@sohu.com

Different approaches have been studied for modeling and control of the fluid dispensing system. In industries, dispensing control and analysis are heuristic and experience-based, whereas in academia, the complete simulation of the dispensing process is a complex work requiring a large amount of computation. Since the fluid dynamics is described by the partial differential equations, the model simulation requires either finite element or finite volume method[4]. Furthermore, the adhesive used for dispensing is often epoxy, which is classified as a non-Newtonian fluid[5] and is difficult to model. So far, the practical research has focused on the analytical approach of modeling the dispenser as a pipe flow by assuming the adhesive as a Newtonian fluid[2,6,7]. However, the results that work for the Newtonian fluid usually do not work for the non-Newtonian fluid[4]. Chhabra[8] suggested an analytical method to include the effects of sudden changes in cross-section for the non-Newtonian fluid, but the results may not be easily incorporated in the control algorithm. The real-time control of the fluid dispensing has been studied by using different technologies and methods, such as extra sensing technology[9], knowledge-based experience[10], statistic process control (SPC) method[11], and decoupling control concept[12]. However, without a good process model, it is still difficult to achieve a high-precision performance. Recently, a simple model-based iterative off-line control method was proposed by regulating the air pressure[6]. Although it achieves good performance in a lab environment, practically, it is difficult to be realized because the pressure may not be an efficient control variable in the real-time dispensing process.

It is noted that most constructed models are black-box models or empirical models, which are based on the measured input and output data. However, for the proper controller design, a physical model or its combination with the empirical models could be very useful. Many models are developed from the physics background and evaluated for improving the dispensing performance. Chen[13] developed a model with partial differential equations to simulate the flow rate of the dispensing and its shape on the board.

Although the simulation results are good compared with experimental data, the results are only for the power-law fluid. Further comparison with the numerical computation has shown the incapability of the analytical method in modeling the non-Newtonian fluid dispensing[4]. Even though the most recent modeling work has taken air compressibility into account[14], the analytical model of the fluid dynamics is still more critical. The over-simplification of the fluid model will cause a larger approximation error.

In this paper, the dispensing time is introduced as the compensatory variable, which is more quick and effective. A dispensing fluid flow rate model of non-Newtonian fluid is delivered and presented with the sum of Bessel serials. Based on this simple and effective model, a realistic model-based control is developed to achieve a robust dispensing performance. Both simulation and real experiment show that the dispensing consistency is greatly improved.

2 Modeling dispensing flow rate

As shown in Fig. 2, since the syringe inner diameter is much larger than that of the needle, and the very small amount of fluid is dispensed in every dispensing cycle, the fluid variation in syringe can be neglected in each cycle. Approximately, the flow rate model can be developed from the syringe tip.

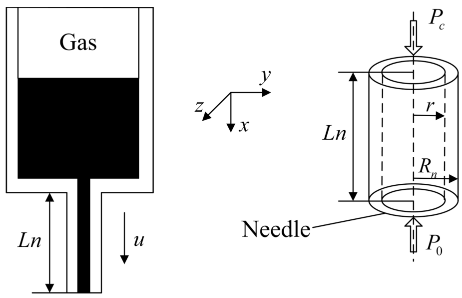

Fig. 2 Structure of the syringe

In order to model the fluid flow rate in the needle, consider the needle as a rigid pipe with a small diameter. The non-Newtonian fluid dynamic motion in it can be described by a general Navier-Stokes (N-S) equation as follows[15]:

$$\rho\left(\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}\right)=-\frac{\partial P}{\partial x}+\rho g+\eta\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right) \quad (1)$$

where u − fluid velocity

ρ − fluid density

η − fluid apparent viscosity

g − gravitational acceleration.

Assume the x-direction is the axis direction of the needle and that

1) The fluid is incompressible.

2) There is no slip between the fluid and the needle wall.

3) The fluid is fully developed (i.e., $(\partial u/\partial x) = 0$ and $(\partial^2 u/\partial x^2 = 0)$.

4) No gravitational effect.

Based on the above assumptions, (1) can be written as

$$\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}-\frac{\rho}{\eta}\frac{\partial u}{\partial t}=\frac{1}{\eta}\frac{\partial P}{\partial x}. \quad (2)$$

Since gravity is omitted then $\rho g \approx 0$. The fluid is fully developed, which means $\partial P/\partial x = (P_c - P)/Ln$, Ln is the length of the needle, and P_0 is the atmosphere pressure. Let $P_c - P_0 = \Delta P$. The pole coordinate (2) is changed into

$$\frac{\partial^2 u}{\partial r^2}+\frac{1}{r}\frac{\partial u}{\partial r}-\frac{\rho}{\eta}\frac{\partial u}{\partial t}=\frac{\Delta P}{\eta Ln}. \quad (3)$$

Let $\zeta = r/R_n$ $(0 \le \zeta \le 1)$, and R_n be the internal radius of the needle. Then we have

$$\frac{\partial^2 u}{\partial \zeta^2}+\frac{1}{\zeta}\frac{\partial u}{\partial \zeta}-\frac{\rho R_n^2}{\eta}\frac{\partial u}{\partial t}=\frac{\Delta P}{\eta Ln}R_n^2. \quad (4)$$

At first we consider the homogeneous style of (4), that is,

$$\frac{\partial^2 u}{\partial \zeta^2}+\frac{1}{\zeta}\frac{\partial u}{\partial \zeta}-\frac{\rho R_n^2}{\eta}\frac{\partial u}{\partial t}=0. \quad (5)$$

To find the solution of (5), the method of separation of variables is used. Let fluid velocity $u(\zeta,t)$ be

$$u(\zeta,t)=\psi(\zeta)T(t). \quad (6)$$

Substituting (6) into (5) yields

$$\frac{\psi''(\zeta)+\frac{1}{\zeta}\psi'(\zeta)}{\psi(\zeta)}=\frac{\rho R_n^2}{\eta}\frac{T'(t)}{T(t)}=-\beta^2 \quad (7)$$

where β is a constant. Equation (7) can be written as

$$\zeta^2\psi''(\zeta)+\zeta\psi'(\zeta)+\zeta^2\beta^2\psi(\zeta)=0 \quad (8a)$$

and

$$T'(t)+\frac{\eta\beta^2}{\rho R_n^2}T(t)=0. \quad (8b)$$

Equation (8a) is Bessel equation of the first kind of zero order. Because there is no slip between the fluid and the needle wall, when $r = R_n$, the fluid velocity should be nil, which means $\psi(1) = 0$; besides, at the symmetrical axes of the needle, the fluid velocity should be finite, that is $|\psi(0)| < \infty$. Solving (8a) together with the two boundary conditions discussed above, we can obtain the general solution:

$$\psi(\zeta)=\sum_{i=1}^{\infty}J_0(\mu_i^{(0)}\zeta) \quad (9)$$

where $J_0(\cdot)$ is Bessel function of the first kind of zero order and $\mu_i^{(0)}$ is the i-th zero. Based on the characteristic of the Bessel function, assume the solution of $u(\zeta,t)$ to be

$$u(\zeta,t)=\sum_{i=1}^{\infty}T_i(t)J_0(\mu_i^{(0)}\zeta). \quad (10)$$

Substituting (10) into (4), and combining the result with (8a), we get

$$\sum_{i=1}^{\infty}\left[\frac{\rho R_n^2}{\eta}T_i'(t)+(\mu_i^{(0)})^2T_i(t)\right]J_0(\mu_i^{(0)}\zeta)=-\frac{\Delta P}{\eta Ln}R_n^2. \quad (11)$$

Thus

$$\frac{\rho R_n^2}{\eta}T_i'(t)+(\mu_i^{(0)})^2T_i(t)=-\frac{2\Delta P R_n^2}{\eta Ln\mu_i^{(0)}J_1(\mu_i^{(0)})}. \quad (12)$$

Solving (12), T_i is obtained as follows:

$$T_i(t) = C_1 \exp(-\frac{\eta(\mu_i^{(0)})^2}{\rho R^2}t) - \frac{2\Delta P R_n^2}{\eta Ln(\mu_i^{(0)})^3 J_1(\mu_i^{(0)})}. \quad (13)$$

For the dispensing process, when the dispensing time $t = 0$, the fluid velocity should be zero, which means $T(0) = 0$, thus we can get the constant C_1, i.e.,

$$C_1 = \frac{2\Delta P R_n^2}{\eta Ln(\mu_i^{(0)})^3 J_1(\mu_i^{(0)})}. \quad (14)$$

Then the flow velocity $u(\zeta, t)$ is expressed as

$$u(\zeta,t) = \frac{2\Delta P R_n^2}{\eta Ln} \cdot \sum_{i=1}^{\infty} \left(1 - \exp(-\frac{\eta(\mu_i^{(0)})^2}{\rho R_n^2}t)\right) \frac{J_0(\mu_i^{(0)}\zeta)}{(\mu_i^{(0)})^3 J_1(\mu_i^{(0)})}. \quad (15)$$

The dispensing flow rate Q is the integral of the velocity, i.e.,

$$Q = \int_0^1 2\pi\zeta u(\zeta,t)d\zeta = \frac{4\pi\Delta P R_n^2}{\eta Ln} \sum_{i=1}^{\infty} \frac{1}{(\mu_i^{(0)})^4} \left(1 - \exp(-\frac{\eta(\mu_i^{(0)})^2}{\rho R^2}t)\right). \quad (16)$$

Then the dispensing volume in a dispensing cycle t_c is

$$V = \int_0^{t_c} Q dt = \frac{4\pi\Delta P R_n^2}{\eta Ln} \sum_{i=1}^{\infty} \frac{1}{(\mu_i^{(0)})^4} \cdot \left(t_c + \frac{\rho R_n^2}{\eta(\mu_i^{(0)})^2}\left(\exp(-\frac{\eta(\mu_i^{(0)})^2}{\rho R_n^2}t_c) - 1\right)\right). \quad (17)$$

From (17) it can be found that when the adhesive is selected and the dispensing conditions are fixed (e.g. R_n, Ln, ρ, and η are invariable), the dispensing flow rate and the volume are mainly decided by the dispensing time and the pressure.

3 Dispensing control

As mentioned above, the volume dispensed is affected by many factors. The gas compressibility is one of the major factors for the inconsistent dispensing. As more fluid is dispensed out of the syringe, the smaller the pressure will be generated inside the syringe in the dispensing cycle, and thus the smaller the volume will be dispensed. Obviously, the pressure compensation is required to cancel the effects of gas compressibility. However, it is difficult for pressure compensation because the pressure adjustment is impractical in the real-time dispensing due to its slow response and the difficult implementation. Fortunately, the dispensing model developed in the previous section can accurately estimate the fluid amount dispensed, which makes the model-based control or compensation with the dispensing time feasible.

3.1 Controller design

In theory, it is possible to design a complex control algorithm; however, it is impossible to apply it in practice due to the physical limitation. Firstly, the resolution of the dispensing time t (interval for keeping the valve opening) is very coarse due to the hardware limitation of the valve. An elegant control action cannot show its advantages under the coarse actuation. Secondly, the dispensing system is one of the major units in the die-bonding machine. It has to share the computation resources with other parallel units like vision system, x-y table motion, bond head motion, *etc.* Only a few milliseconds are available for the dispensing computation.

Because it is a slow process between runs, a proportional-integral (PI) control would be suitable. Furthermore, since the initial dispensing time, which will be discussed in the next section, should be calibrated before really dispensing, and the dispensing time only needs to be fine-tuned when the variation of the fluid amount dispensed occurs, an incremental adjustment, i.e., the integral control, is the best option as shown in Fig. 3, where the proportional control is not required (set K_P=0). The integral control controller can be implemented in the special discrete form as given below:

$$t_k = t_0 + \sum_{i=1}^{k} \Delta t_i \quad (18)$$

with t_k – the dispensing time t of the k-th cycle,

t_0 – the initial dispensing time discussed in the next section,

Δt_i – the incremental time at i-th step to provide the integral action.

$$\Delta t = K_I(\Delta V) = K_I(V - V_m) \quad (19)$$

where V is the fluid volume estimated from the model, V_m is the fluid volume dispensed, and K_I is integral gain that needs to be determined by experiment. In practice, an SPC unit is used to remove the stochastic variations to make the volume estimation V more reliable.

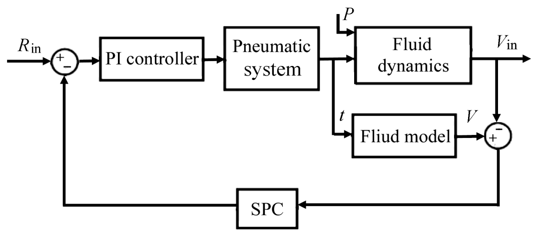

Fig. 3 Configuration of model-based dispensing control system

3.2 Parameter initializing

It is noted that we do not give the dynamics of a pneumatic system. The reason is that the pneumatic system, which includes a pneumatic solenoid valve, a transmit tube and the gas chamber in the syringe, is a nonlinear system[16]. Moreover, the gas compressibility is very difficult to present in the pneumatic system model. Thus, we consider the approximate measurement of the syringe pressure with a pressure transducer connected to the syringe gas chamber. On this condition, it means that the appropriate dispensing pressure and time are unknown before the start of the dispensing. Thus, it is required to initialize the dispensing time beforehand, or else we cannot obtain the desired fluid amount dispensed even if it may be well consistent. In this paper, the dispensing time is initialized by the following calibration process:

1) Select and fix the dispensing pressure P_0, start dispensing with arbitrary dispensing time without PI control.

2) Measure the fluid amount dispensed by a vision system[17], and adjust the dispensing time to make the fluid amount dispensed equal to the desired amount. If P_0 is not appropriate (for example, too much or too little dispensing time is needed to fulfill the requirement $V_{\text{out}} = V_{\text{desired}}$), then adjust them and redo these two steps until the setup is appropriate.

3) If $V_{\text{out}} = V_{\text{desired}}$ is obtained, the corresponding parameter values of the dispensing time t_c and the pressure P_0 are retained as the initial setup parameters under the PI control dispensing condition.

3.3 Model-based control

After obtaining dispensing time, the dispenser starts working with PI control. This process is still affected by some disturbance and the increase of the gas volume in the syringe with continuous dispensing. These effects can be compensated by modifying the dispensing time through the PI controller.

4 Simulations and experiments

The experimental equipment include an air supply controller provided by ASM Assembly Automation Ltd. HK, a command valve provided by SMC, a transmission line with an internal diameter of 4 mm and a length of 3.6 m, and a dispenser involving a syringe and a needle. Besides, a pressure transducer is connected to the syringe chamber to sample its pressure. Other experiment parameters are listed in Table 1.

Table 1 Experimental parameters setup

Parameter	Values
Air pressure	1.0 E+5 Pa
Temperature	25 ^{o}C
Fluid viscosity	12 560 mPa.s
Distance between needle and PCB	1.6 E-4 m
Length of needle	1.8 E-2 m
Syringe	10 cm^3
Internal diameter of needle	6.4 E-4 m

4.1 Model validation

The instantaneous flow rate is extremely difficult to measure directly, but the average fluid flow rate can be obtained easily by using the dispensing time to divide the corresponding fluid amount dispensed. The average fluid flow rate is simulated and measured as shown in Fig. 4. Fig. 4 (a) shows the simulation result of the fluid flow rate. It can be found that the fluid flow rate increases with the dispensing pressure. Meanwhile it increases with the dispensing time before the pressure gets steady. When $t_c \geq 60$ ms, the syringe pressure works in steady state and the fluid flow rate does not change with the dispensing time. Fig. 4 (b) shows the comparison results of experiments and simulations for three different dispensing pressures with 140 kPa, 160 kPa and 180 kPa. It shows that the model developed in this paper can predict the flow rate with significant precision.

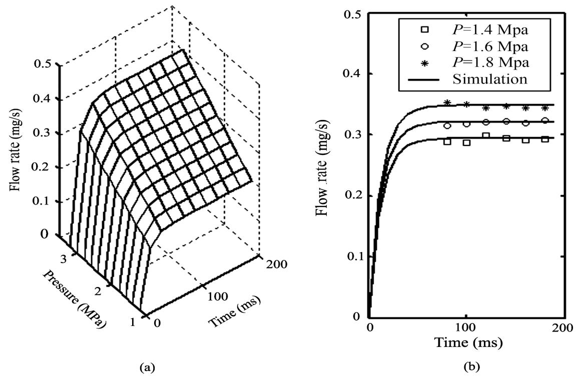

Fig. 4 Simulation of non-Newtonian adhesive flow rate in dispensing

4.2 Model-based control

In this section, the comparison of dispensing with and without control is presented. This comparison includes two conditions, called condition I and condition II. Condition I is carried out with a same fluid level left in the syringe which means comparing cycle by cycle. Condition II denotes that the left fluid is different, which aims to compare the compensating ability of model-based control to the influence of gas compressibility. To reduce the random error, the total amount of the fluid dispensed in ten cycles is measured and then the average is taken to represent the fluid amount of one cycle. Additionally, silicon oil (viscosity = 12 560 mPa.s) is selected as the dispensing material.

The two experiments are carried out under the condition of Table 1. The time increment Δt based on last cycle is presented (see Tables 2 and 3). It is seen that a significant improvement of the consistency in flow rate has been achieved for both fixed fluid level and changeable level by introducing the model-based control strategy. The real dispensing times for different fluid volumes left in the syringe are shown in Fig. 5.

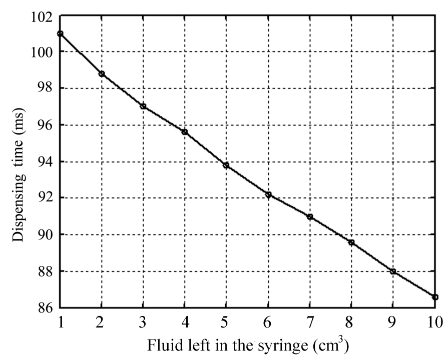

Fig. 5 Dispensing time versus fluid amount left in syringe

Table 2 Dispensing result with and without model-based control for the same fluid left in the syringe

Sample number	Desired dot amount (mg)	Uncontrolled Δt (ms)	Uncontrolled Real dot amount (mg)	Controlled Δt (ms)	Controlled Real dot amount (mg)
1	0.012	0	0.0118	0	0.0118
2			0.0116	0.2	0.0112
3			0.0124	0	0.012
4			0.0142	0.2	0.012
5			0.014	0.2	0.0126
6			0.0112	-0.4	0.0128
7			0.0108	-0.4	0.0118
8			0.0134	0.2	0.013
9			0.0142	-0.4	0.0124
10			0.0138	0	0.0126

Table 3 Dispensing result with and without model-based control for different fluid left in the syringe

Fluid level (cm^3)	Desired dot amount (mg)	Uncontrolled Δt (ms)	Uncontrolled Real dot amount (mg)	Controlled Δt (ms)	Controlled Real dot amount (mg)
10	0.018	0	0.0178	0	0.0178
9			0.0172	1.4	0.0188
8			0.0166	1.6	0.019
7			0.0152	1.4	0.0184
6			0.0146	1.2	0.0172
5			0.0144	1.6	0.0184
4			0.0136	1.8	0.017
3			0.0132	1.4	0.0182
2			0.013	1.8	0.017
1			0.0124	2.2	0.0172

To measure the degree of the improvement, the standard deviation σ and the variation var are used, which are respectively given by

$$\sigma = \sqrt{\frac{\sum\limits_{j=1}^{n}(V_j - \bar{V})^2}{n}} \tag{20}$$

and

$$var = \frac{\max\{V_j\} - \min\{V_j\}}{\bar{V}} \tag{21}$$

where $j = 1, 2, 3, \cdots n$, $\bar{V}$ is the mean of the sample V_j and n is the sample number ($n = 10$ for the two experiments). From (20) and (21), it is seen that variation is the prominence to the maximal fluid amount wave, which is an important index to appraise dispensing quality. The calculation results for conditions I and II are given in Tables 4 and 5, respectively.

From Tables 4 and 5, it can be seen that the mean of the actual dispensing amounts with model-based control closely approaches the desired amounts. It is also observed that the sample deviations are significantly reduced from 0.122% to 0.04% for condition I, and from 0.177% to 0.072% for condition II; besides, the maximal deviations are significantly reduced from 26.3% to 9.7% for condition I, and from 36.5% to 11.2% for condition II. The result means whether at the same or at obviously changeable fluid level, the model-based control can improve the dispensing consistency effectively.

Table 4 Statistical comparison of dispensing results with and without model-based control for the same fluid level left in the syringe

	Desired dot amount (mg)	Mean (mg)	Standard deviation (%)	Variation (%)
Uncontrolled	0.012	0.0129	0.122	26.3
Controlled		0.0123	0.04	9.7

Table 5 Statistical comparison of dispensing results with and without model-based control for different fluid levels left in the syringe

	Desired dot amount (mg)	Mean (mg)	Standard deviation (%)	Variation (%)
Uncontrolled	0.018	0.0148	0.177	36.5
Controlled		0.0179	0.072	11.2

5 Conclusions

A flow rate model based on non-Newtonian fluid is developed with Bessel function for the flow rate estimation and is further applied to the fluid dispensing process to estimate the volume dispensed. The effectiveness of the developed model is evaluated in both simulation and experiment. A PI controller is introduced to compensate the deviation of the fluid amount dispensed yielded from the gas compressibility. The results indicate that the model developed in this paper is promising for representing the flow rate in time-pressure dispensing processes, and a better performance is achieved by using the proposed model-based dispensing control scheme.

References

[1] R. Bush. Matching Fluid Dispensers to Materials for Electronics Applications. *Electronic Packaging & Production*, vol. 37, no. 9, pp. 6–62, 1997.

[2] A. Razban. Intelligent Control of an Automated Adhesive Dispensing Cell. Ph.D. dissertation, Imperial College, London, UK, 1993.

[3] D. Dixon. Practical Issues Concerning Dispensing Pump Technologies. *Circuits Assembly*, vol. 8, no. 8, pp. 36–40, 1997.

[4] Y. P. Hong, H. X. Li. Comparative Study of Fluid Dispensing Modeling. *IEEE Transactions on Electronics Packaging Manufacturing*, vol. 26, no. 4, pp. 273–280, 2003.

[5] P. Kropp. Problems with High Speed Adhesive Dispensing. In *Proceedings of 7th International SAMPE Electronics Conference*, Parsippany NJ, USA, pp. 487–493, 1994.

[6] X. B. Chen, W. J. Zhang, G. Schoenau, B. Surgenor. Offline Control of Time-pressure Dispensing Processes for Electronics Packaging. *IEEE Transactions on Electronics Packaging Manufacturing*, vol. 26, no. 4, pp. 286–293, 2003.

[7] A. Razban, B. L. Davies. Analytical Modeling of the Automated Dispensing of Adhesive Materials. *Journal of Adhesion Science and Technology*. vol. 9, no. 11, pp. 1435–1450, 1995.

[8] R. P. Chhabra. J. F. Richardson. *Non-Newtonian Flow in the Process Industries: Fundamentals and Engineering Applications*, Butterworth-Heinemann, Oxford, 1999.

[9] A. Razban, O. S. Sezgin, B. L. Davies. Real Time Control of Automated Adhesive Dispensing. In *Proceedings of the 3rd International Conference on Software Engineering for Real Time Systems*, Cirencester, UK, pp. 145–150, 1991.

[10] R. Chandraker, A. A. West, D. J. Williams. The Knowledge Based Control of Adhesive Dispensing for Surface Mount Device Assembly. *IEEE Transactions on Components, Hybrids and Manufacturing Technology*, vol. 13, no. 3, pp. 516–520, 1990.

[11] R. Spinazzola. Statistical Process Control Applied to Automate Dispense of Silver Filled Epoxy for Commercial Millimeter Wave Multichip Module. In *Proceedings of IEEE International Conference on Multi-chip Modules*, Denver, USA , pp. 228–233, 1997.

[12] H. X. Li, S. K. Tso, H. Deng. A Conceptual Approach to Integrate Design and Control for the Epoxy Dispensing Process, *Advanced Manufacturing Technology*, vol. 17, no. 9, pp. 677–682, 2001.

[13] X. B. Chen, G. Schoenau, W. J. Zhang. Modeling of Time-pressure Fluid Dispensing Processes. *IEEE Transactions on Electronics Packaging Manufacturing*, vol. 23, no. 4, pp. 300–305, 2000.

[14] X. B. Chen, G. Schoenau, W. J. Zhang. Modeling and Control of Dispensing Processes for Surface Mount Technology. *IEEE/ASME Transactions on Mechatronics*, vol. 10, no. 3, pp. 326–334, 2005.

[15] C. J. Sunil, Y. C. Lam, F. Y. C. Boey, A. I. Y. Tok. Power Law Fluid and Bingham Plastics Model for Ceramic Tape Casting. *Journal of Materials Processing Technology*, vol. 120, no. 1-3, pp. 215–225, 2002.

[16] E. Richer, Y. Hurmuzlu. A High Performance Pneumatic Force Actuator System: Part 1 - Nonlinear Mathematical Model. *Journal of Dynamic Systems, Measurement and Control, Transactions of the ASME*, vol. 122, no. 3, pp. 416–425, 2000.

[17] A. A. West, D. J. Williams, C. J. Hinde. Experience of the Application of Intelligent Control Paradigms to Real Manufacturing Processes. *Proceedings of the Institution of Mechanical Engineers, Part I, Journal of Systems & Control Engineering*, vol. 209, no. 4, pp. 293–308, 1995.

Cong-Ping Chen received his B.Sc. and M.Sc. degrees in mechatronic engineering from Kunming University of Science and Technology of China in 1999 and 2002, respectively. He is currently a Ph.D. candidate in mechatronic engineering at Huazhong University of Science and Technology of China.

His research interests include automatic fluid dispensing, process control, and machine vision.

Han-Xiong Li received his Ph.D. degree in electrical engineering from University of Auckland, New Zealand, in January of 1997, M.Eng. degree in electrical engineering from Delft University of Technology in the Netherlands in 1991, and B.Eng. degree from National University of Defence Technology in China in 1982. He is an associate professor at the Department of Manufacturing Engineering and Engineering Management, City University of Hong Kong. He is a Chang Jiang Scholar in Central South University. He was awarded the Distinguished Young Scholar Fund by the China National Science Foundation in 2004. He also is an associate editor for *IEEE Transactions on Systems, Man, and Cybernetics - Part B.*

His research interests include intelligent control and learning, process modeling and control, complex distributed parameter system, and electronics packaging process.

Han Ding received his Ph.D. degree from Huazhong University of Science and Technology (HUST) in 1989.

He was supported by Alexander von Humboldt Foundation, and worked at University of Stuttgart, Germany from 1993 to 1994. From 1994 to 1996, he worked at School of Electrical and Electronic Engineering, Nanyang Technological University, Singapore. He was the recipient of National Distinguished Youth Scientific Fund of China (former Premier Fund) in 1997. He has published more than 70 papers in international journals and proceedings. From 1997 to 2001, he was a professor of HUST. He is now a Yangtze Distinguished Professor (Special Appointment of the Yangtze Scholars Award Plan) of Shanghai Jiao Tong University. He is a senior member of IEEE.

His research interests include application of computational geometry to design and manufacturing, robot technology and application, computational intelligence, computational manufacturing, and virtual prototyping.