

## A Study on the Comparison of Solderability Assessment

B. Salam\*, N.N. Ekere\* and J. P. Jung\*\*

\*University of Salford  
 School of Aero., Civil and Mech. Eng., Salford-M54WT, UK  
 (presently University of Greenwich, UK)

\*\*University of Seoul,  
 Dept. of Material Sci. and Eng., 90Junnong-dong, Dongdaemun-gu, Seoul 130-743, Korea

### Abstract

The purpose of solderability assessment is to predict the effectiveness of soldering process. It is important for companies pursuing zero defects manufacturing because poor solderability is the major cause of two third of soldering failures. The most versatile solderability method is wetting balance method. However, there exist so many indices for wettability in the wetting balance test e.g. time to reach 2/3 values of maximum wetting force, time to reach zero wetting force, maximum withdrawal force. In this study, three solderability assessment methods, which were the maximum withdrawal force, the wetting balance and the dynamic contact angle (DCA), were evaluated by comparing each other. The wetting balance technique measures the solderability by recording the forces exerted from the specimen after being dipped into the molten solder. Then the force at equilibrium state can be used to calculate a contact angle, which is known as static contact angles. The DCA measures contact angles occurred during advancing and withdrawing of the specimen and the contact angles are known as dynamic contact angles. The maximum withdrawal force uses the maximum force during withdrawal movement and then a contact angle can be calculated. In this study, the maximum withdrawal force method was found to be an objective index for measuring the solderability and the experiment results indicated good agreement between the maximum withdrawal force and the wetting balance method.

### 1. Introduction

Solderability is the ability of a surface to be wet by molten solder. It plays an essential role in the modern electronic industry, and hence also in the enormous range of products. The reliable mass production of soldered joints is thus now of paramount importance, since any item of electronic equipment can only be as reliable as the joints that

constitute its assembly. These concerns are emphasised by the increasing speed of production and the trend towards further product miniaturisation, which make routine inspection more difficult. The move towards achieving "zero defect" production requires a thorough knowledge of the basic concepts of solderable surfaces, and the various techniques that can be used to test the solderability at various stages of production.

One important condition for achieving a good solderability is that the surface must have a good wettability. Good wettability results in good solderability, which means the formation of a uniform, smooth, unbroken, adherent coat of solder on the base metal. Wettability is determined by contact angle, as seen in Fig. 1. The contact angle that is below  $90^\circ$  indicates wetting ( $\theta = 0$  corresponding to perfect wetting) and the opposite the contact angle that is above  $90^\circ$  is a sign of poor wetting ( $\theta = 180$  corresponding to non-wetting).

Theoretically, the interfacial surface forces dictate the shape of the molten solder. The resulting surface tensions and their effect on wetting are best illustrated by the Young's relation, which defines the contact angle given by:

$$\frac{\gamma_{sv} - \gamma_{sl}}{\gamma_{lv}} = \cos\theta \quad (1)$$

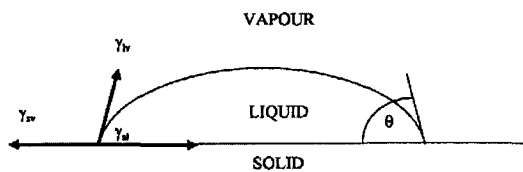


Fig. 1 Surface Tension and Contact Angle by a Liquid Droplet<sup>6</sup>

Where the symbols  $\gamma_{sv}$ ,  $\gamma_{sl}$ , &  $\gamma_{lv}$  refer to the solid-vapour, solid-liquid and liquid-vapour surface tension, respectively. For optimum wetting, the solid-vapour surface tension must be maximised, and the solid-liquid and liquid-vapour surface tension must be kept minimised<sup>2</sup>. For the solid-vapour surface tension, the value can be increased by applying flux to remove the oxides and contaminants on the substrate<sup>2</sup>. For the liquid-vapour surface tension, the value is relatively constant because the liquid-vapour surface tension is referred

to as the surface tension of the solder, which the value is a function of the solder composition, and the flux<sup>2</sup>. The solid-liquid surface tension is influenced by the chemical reaction between the liquid and the solid substrate such as the formation of the intermetallic compound layer<sup>2</sup>.

Some techniques to measure solderability such as solder dip method, area-of-spread test, meniscus shape method, wetting balance test and dynamic contact angles (DCA) have been introduced. The last two techniques are known as force method and among them, the wetting balance test has been the most commonly used in the electronic industries. However, there exist so many indices for wettability in the wetting balance test, e.g. time to reach 2/3 values of maximum wetting force, time to reach zero wetting force, and maximum withdrawal force. The maximum withdrawal force that is mentioned at the end has not been fully introduced. Therefore, in this study, the maximum withdrawal force technique method for measuring the contact angles was compared to the static measurement, the wetting balance technique and the dynamic measurement, the DCA to find relatively more objective method.

## 2. Theory

### 2.1 Wetting Balance Method

The wetting balance method measures the contact angle by immersing the specimen into a bath of molten solder. The immersion speed is set at a controlled rate and the molten solder is held at constant desired temperature. The specimen is connected to the sensitive force measurement, which a computer will continuously record the forces. The result of the measurement is a graph of

forces against time, which is called wetting balance curve.

For use with surface mount components, the specimen is first fluxed and hung over the solder bath for a predetermined time such that the flux is effectively preheated by convection from the molten solder bath. The specimen is then immersed, usually at a speed of 2-5mm/s, to predetermined depth, usually about 3mm, and held in that position for a specific time, usually about 5s. The force experienced by the specimen as a function of time is recorded.

In this method, the specimen is made in such that the thickness is much smaller than the other two dimensions. Neglecting the weight of the specimen, the vertical force exerted on the specimen is as followed:

$$F = P \cdot \gamma_w \cdot \cos\theta \quad (1a)$$

In practice, a solderability index is time, not a contact angle. The time at two third of the maximum force or the time when the force is zero is commonly used indices. Short time indicates good wetting and long time means poor wetting. However, the contact angle number is still necessary to determine the degree of wetting, which equation 1a can be used to calculate the contact angle.

## 2.2 Dynamic Contact Angles (DCA)

The dynamic method is referred to as the DCA technique. It is referred as Wilhelmy method. With this method a flat plate is held vertically on an electrobalance and beaker of liquid is moved up (immersion) and subsequent emersion at a predetermined rate as shown in Fig. 2. The electrobalance, which is a very sensitive force measurement ( $0.05 \mu\text{N}$ ), will measure forces, which exerted on the flat plate by the liquid. A computer will record

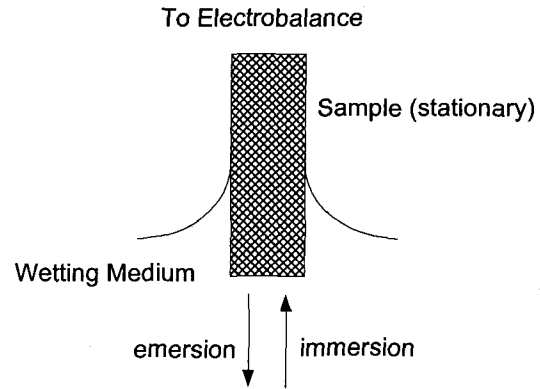


Fig. 2 Dynamic Contact Angle Measurement<sup>6</sup>

and plot the forces against time and immersion/emersion depth.

The measured force is used to determine the contact angle and the relationship of them is illustrated in equation 2. The first term of the equation is the wetting force of the liquid on the solid, the second term is the buoyancy force and the third term is the weight of the solid in air.

$$F_A = F_R = \gamma_w \cdot P \cdot \cos\theta - \rho \cdot g \cdot V_b + mg \quad (2)$$

Contact angles are calculated when the stage moves up (advancing angle) and when it moves down (receding angle) and has a range from  $0^\circ$  (complete wetting) to  $180^\circ$  (complete non-wetting). The difference between the two contact angles is a property of the surfaces called the contact angle hysteresis. The lower the hysteresis the better the wettability. Hysteresis is produced by surface roughness, contamination, heterogeneity and functional group orientation. For complete wetting, hysteresis must be zero. The different in behaviour result from the fact that the meniscus traverses over a non-wetted region during the advancing stage and an already wetted surface during the receding stage.

2. 3 Maximum Withdrawal Force method

Withdrawal force method has been reported by Park et. al.<sup>3-5)</sup>. The wetting balance result is known as wetting force-time curve. In the wetting force-time curve, the force starts downward (the initial non-wetting) and quickly reaches the minimum. Then as the sample is wet, the force ascends rapidly, crossing zero and exponentially approaching its equilibrium value. After this, the force remains constant while the sample is hold steady. As the sample is lifted from the solder bath, the force ascends upward instantly and then descends rapidly. The withdrawal force curve is measured starting from the moment the sample is lifted, as seen in Fig. 3. d.

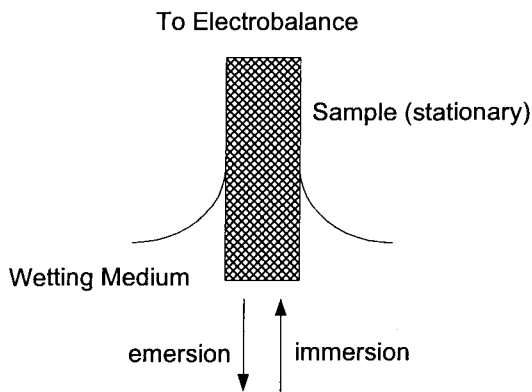


Fig. 3 Wetting Force-Time Curve (d-f = withdrawal force curve)<sup>3)</sup>

In the withdrawal force curve, the steep rise of the force indicates the decrease of buoyancy force by withdrawing process, and at the peak of the curve, the solder has slipped to the specimen edge, as seen in Fig 4. That point is known as maximum withdrawal force. At that point, the sample is no longer affected by buoyancy force and the contact angle falls down to zero. However, the liquid is still attaching to the specimen base and produces a

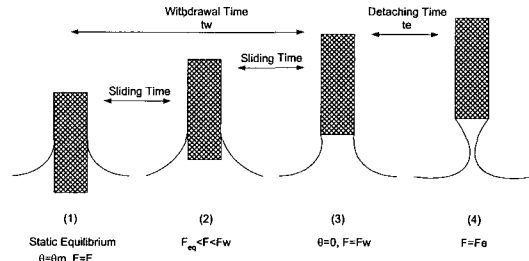


Fig. 4 Mechanism of the Withdrawal Curve<sup>3)</sup>  
force that is opposite to the buoyancy force. The equation at that point can be written as follow :

$$F_w = P_w \cdot \gamma + \rho \cdot g \cdot V_u \tag{3}$$

After measuring the maximum withdrawal force, the surface tension and the contact angle can be calculated using the following equations :

$$\gamma = \frac{P_w - \rho \cdot g \cdot V_u}{P_w} \tag{4}$$

$$\cos\theta = \frac{P_w \cdot (F_{eq} + \rho \cdot g \cdot V_b)}{P_{eq} \cdot (F_w - \rho \cdot g \cdot V_u)} \tag{5}$$

However there is potential subjective measurement in this technique that is the calculation of  $V_u$  as follow (as seen in Fig. 5) :

$$V_u = H \cdot w \cdot t_h \tag{6}$$

The meniscus height [H] as one of the above equation parameter is difficult to measure since it is too small to be seen by naked eyes. To minimise the subjective of the measurement, the value of the meniscus height [H] is calculated by the following

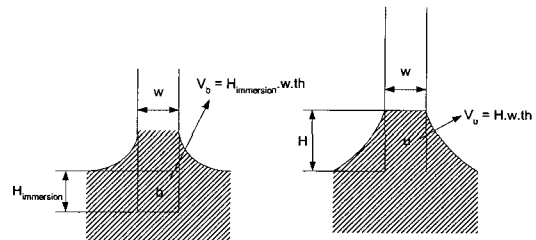


Fig. 5 Illustration of the Parameters of Withdrawal Force Equation

equation (as seen in Fig. 6) :

$$H = \Delta t \cdot V_{\text{withdrawal}} - H_{\text{immersion}} \quad (7)$$

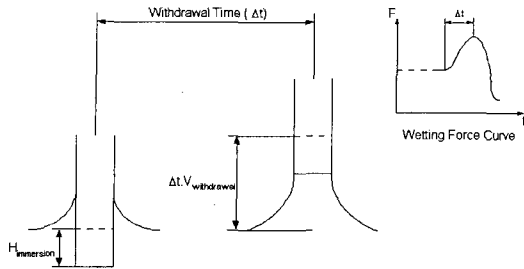


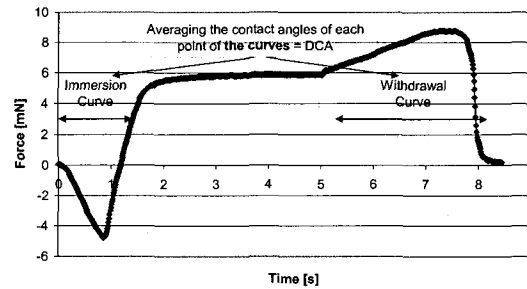
Fig. 6 Illustration of the Parameters for Calculating Meniscus Height (H)

### 3. Experimental Procedure

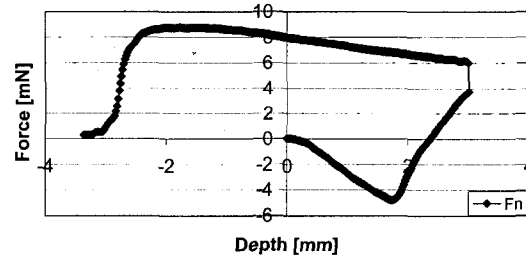
The wetting balance tests were performed with SAT-5000. Cu coupons were used as vertical flat specimens and their sizes were 20×7×0.3mm. To simulate the real-life soldering process, eutectic Sn-Pb and Sn-3.5Ag alloys were used as the liquid probe. The immersion and withdrawal speed were 2, 5 & 10 mm/s, immersion depth 3 & 4 mm and immersion time 5 seconds. The experiment temperature varied from 198 to 260 °C. Before dipping, the Cu coupon was cleaned with 5% HCl, ethanol and then RMA flux was applied with preheating for one minute by placing it over the melting solder. In this experiment, we assume that the density of the solder is 8.5 gr/cm<sup>3</sup> and the density of the Cu coupon is 8.93 gr/cm<sup>3</sup>.

The maximum withdrawal force and DCA results were obtained from the wetting balance test. A maximum withdrawal force can be acquired from the highest point of a withdrawal force curve of a wetting balance curve, as seen in Fig. 3. For DCA results, the wetting balance curves need to be converted. A wetting balance-to-DCA conversion can

be done by averaging contact angles of immersion and withdrawal curves of a wetting balance curve, as seen in Fig. 7a. The result of the conversion from wetting balance to DCA can be seen in figure 7b.



(a)



(b)

Fig. 7 a) Illustration of wetting balance-to-DCA conversion b) The result of the conversion from wetting balance to DCA

### 4. Results and Discussion

Table 1, Fig. 8a and Fig. 8b show the contact angles measured by the Wetting Balance, the Maximum Withdrawal Force and the DCA. Most of the data in Table 1, Fig. 8a and Fig. 8b show that there is good agreement between the maximum withdrawal force and the wetting balance but not the DCA. For examples, as seen in Table1, at the speed of 2mm/s, the contact angles measured by the wetting balance are about 42–46° and those measured by the maximum withdrawal force are around 45–49°. However, those measured by the DCA are around

Table 1. Result of the contact angles measured from the Wetting Balance, the Maximum Withdrawal DForce and the DCA.

No.	Solder Alloy	Speed [mm/s]	Temperature [C]	Contact Angle [degree]		
				Wetting Balance	DCA	Withdrawal Force
1	Sn-37Pb	2	230	45.5	75.1	44.7
2	Sn-37Pb	2	240	45.5	70.5	48.2
3	Sn-37Pb	2	250	44.7	69.2	49.0
4	Sn-37Pb	2	260	42.1	67.4	44.6
5	Sn-37Pb	5	198	86.9	76.2	87.7
6	Sn-37Pb	5	208	64.5	71.0	60.3
7	Sn-37Pb	5	218	54.9	68.3	49.5
8	Sn-37Pb	5	228	46.9	66.5	41.9
9	Sn-37Pb	5	230	52.8	76.4	48.2
10	Sn-37Pb	5	240	45.8	65.8	48.2
11	Sn-37Pb	5	250	44.1	66.9	42.5
12	Sn-37Pb	5	260	44.5	65.5	44.4
13	Sn-37Pb	10	230	46.4	78.0	45.6
14	Sn-37Pb	10	240	37.2	76.6	36.4
15	Sn-37Pb	10	250	37.6	76.6	37.8
16	Sn-37Pb	10	260	35.8	73.5	39.8
17	Sn-3.5Ag	5	236	61.7	69.5	62.5
18	Sn-3.5Ag	5	246	53.5	71.6	47.2
19	Sn-3.5Ag	5	256	51.5	67.2	50.7
20	Sn-3.5Ag	5	266	49.7	62.6	48.4

67-75°. The differences between the contact angles measured by the wetting balance and the maximum withdrawal force is small (5%) and the differences between the previous two methods and the DCA are around 50%.

From Table 1, Fig. 8a and Fig. 8b, it can be seen that the contact angles measured by the three methods decreased with increasing temperature in general. For the eutectic Sn-Pb, the contact angles at the dipping speed 5mm/s decrease from 198°C to 230°C and stay approximately similar from 230°C to 260°C, as seen in figure 8a. For the Sn-3.5Ag, the contact angles at dipping speed 5mm/s decreased from 236°C to 266°C. In soldering, these results indicate that the solderability of the soldering process could be improved by increasing the temperature from 198 to 230°C for eutectic Sn-Pb alloy and from 236 to 266°C for Sn-3.5Ag alloy.

Since there is good agreement in the contact angle measured using withdrawal force technique, therefore the results of contact angles can be compared using different dipping speed, as seen in

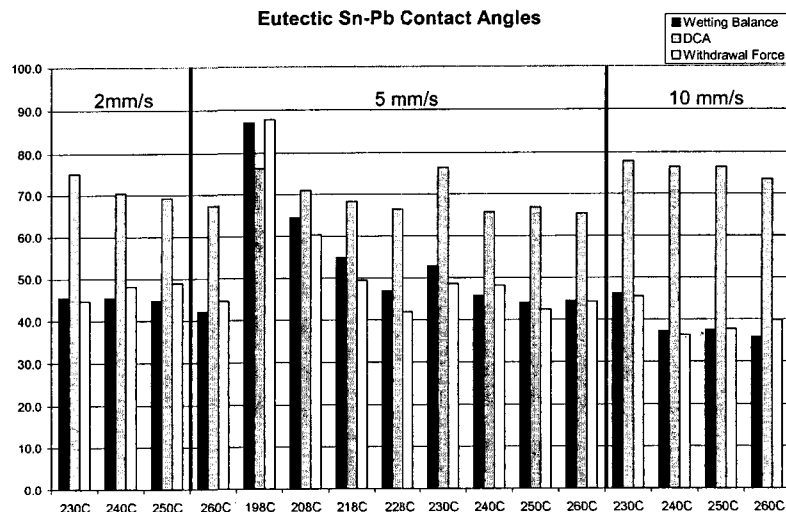


Fig. 8 Comparison of contact angles measured from the Maximum Withdrawal Force, the Wetting Balance, and the DCA for eutectic Sn-Pb alloy.

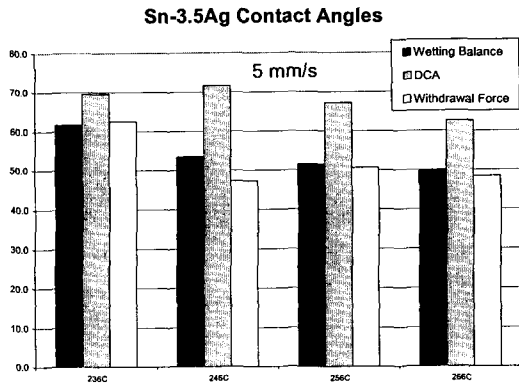


Fig. 8b. Comparison of contact angles measured from the Maximum Withdrawal Force, the Wetting Balance, and the DCA for Sn-3.5 Ag alloy

Fig. 9. The dipping speeds used in this experiment were 2 mm/s, 5 mm/s and 10 mm/s. At 230°C, the effect of the dipping speed towards the contact angles was not so obvious but from 240°C to 260°C, it was clear that the contact angles decreased as speed increased. These results show that the dipping speed affects the contact angle measurement when the temperature reaches above 230°C for the case of eutectic Sn-Pb. However, it seems that the effect of the dipping speed towards the contact angles measured by the three methods was not so great.

The contact angles measured by the three meth-

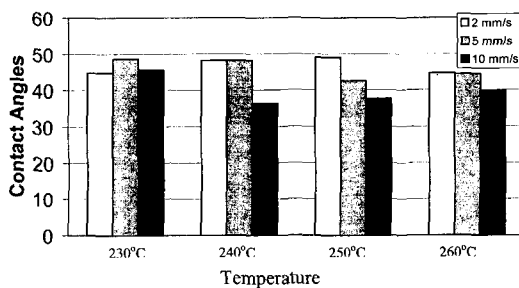


Fig. 9. The effect of dipping speed towards contact angles for eutectic Sn-Pb alloy (measured using the Maximum Withdrawal Force)

ods are affected differently by the temperature changes. For example, as seen in figure 8a, at dipping speed 5mm/s, the decrease rate of the contact angles between 198 °C and 260 °C measured by the wetting balance is similar to those measured by the maximum withdrawal force. The contact angles measured by the both previous methods are parabolically decreased. However, the decrease rate of the contact angles measured by the DCA between 198 °C and 260 °C is smaller than those measured by the previous two methods. The decrease rate of the DCA is almost linear.

The contact angles measured by the wetting balance are static contact angles and those measured by the DCA are dynamic contact angles. The contact angles from the maximum withdrawal force might be static contact angles because during withdrawal, when the fluid reached the edge of the Cu coupon, the viscous deformation became very small. When the viscous deformation becomes very small, the contact angles change to static. This might be explained the reason why maximum withdrawal force's contact angle is similar to wetting balance's contact angle, which is known as static contact angles.

The differences between static and dynamic contact angles are because the augmentation of the viscous drag exerted by the fluid. Our experiment indicates that the difference between the static and the dynamic contact angles can also be attributed to the temperature. The results in figure 8a, at the dipping speed 5mm/s, showed that the differences between static and dynamic contact angles increased with increasing temperature from 198 °C to 230°. In the case of the Sn-3.5Ag alloy, however, as seen in Table 1 and figure8b, the trend was not so clear as Sn-37Pb alloy. Meanwhile, in

figure 8a, at the dipping speed 2mm/s, 5mm/s and 10mm/s, the differences between static and dynamic contact angles are almost similar.

The maximum withdrawal force technique as the tool for solderability measurement offers some benefits, as follows:

1) The withdrawal force can be easily converted to contact angle, which is common figure for wetting index.

2) The capability to calculate the surface tension

Since there is no buoyancy force at the peak of the withdrawal force curve (the maximum withdrawal force), the surface tension of the liquid is easier and more accurate to be calculated. The following Table 2 is the surface tension of the eutectic Sn-Pb and Sn-3.5Ag alloys measured using the maximum withdrawal force and then the surface tension was compared to the reported results. The calculated values from the maximum withdrawal force shows good agreement with the reported ones.

Table 2. Comparison between the maximum withdrawal force and reported surface tension<sup>8, 9)</sup>

Material	$\gamma$ (N/m)	
	Maximum Withdrawal Force	Reported
Eutectic Sn-Pb	0.46 (228°C)	0.42
Sn-3.5 Ag	0.51 (266°C)	0.48

## 5. Summary

Three contact angle measurement methods, which were the maximum withdrawal force, the wetting balance, and the DCA, have been evaluated by comparing each other. In the experiment, the contact angles of the eutectic Sn-Pb and Sn-3.5Ag

solder alloy were measured using the three methods, at different dipping speeds and at different temperature. Contact angles measured by the wetting balance and the maximum withdrawal force show good agreement (5% difference). However, the contact angles from the DCA are higher than those of the previous two methods. One reason of the differences can be because the DCA is dynamic measurement and the other two are static measurement. In addition, withdrawal force method enables to calculate surface tension of molten solder and the calculated value shows nearly good agreement with the other reported values. Therefore withdrawal force technique has been demonstrated as a relatively objective index for measuring the solderability.

## Acknowledgement

The authors are thankful to the STEPI of Korea and British Embassy for their financial support during this study.

## References

1. F.G. Yost, F.M. Hosking, and D.R. Frear, *The Mechanics of Solder Alloy Wetting and Spreading* (1993), New York, Van Nostrand.
2. D.R. Frear, W.B. Jones, and K.R. Kinsman, *Solder Mechanics*, (1991), TMS.
3. J. Y. Park, C.S. Kang, and J.P. Jung, *J. Electron. Mater.* 28, 1256 (1999).
4. J.Y. Park, J.P. Jung, and C.S. Kang, *IEEE trans. CPT* 22, 372 (1999).
5. J. Y. Park, *Doctoral Thesis 67* (2000), Seoul, Seoul National University.
6. G. Takyi, N.N. Ekere, K.G. Snowdon, and C.G.



- Tanner, J. of Electron. Manuf. 9, 233 (1999).
7. C. Lea, A Scientific Guide to Surface Mount Technology (1988), Electrochemical Publications.
8. I. Artaki, A.M. Jackson and P.T. Vianco, J. Electron. Mater. 23, 757 (1994).
9. H. Takao, H. Hasegawa, T. Tsukada, M. Mizuno, K. Yamada, and S. Yamamoto, Proc. 2nd Symp. Microjoining and Assembly Technol. in Electron. 101 (Osaka, Japan: JWS 1999).

### Nomenclature

$F_{eq}$	: Wetting Force during static equilibrium	H	: Meniscus Height during withdrawal
$F_w$	: Maximum Withdrawal Force	$H_{immersion}$	: Meniscus Height during immersion
$F_A$	: Advancing Force	P	: Perimeter
$F_R$	: Receding Force	th	: thickness
		$V_b$	: Buoyancy Volume
		$V_u$	: Volume of liquid below specimen during maximum withdrawal force (see Figure 5)
		$V_{withdraxal}$	: Withdrawal Velocity
		w	: Width
		$\Delta t$	: Time from start withdrawing to maximum withdrawal force (see Figure 6)
		$\gamma_{lv}$	: Liquid-vapour Surface Tension
		$\gamma_{sl}$	: Solid-liquid Surface Tension
		$\gamma_{sv}$	: Solid-vapour Surface Tension
		$\theta$	: Contact Angle
		$\rho$	: Density