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Optimal conditions for the wetting balance test

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ARTICLE INFO

Article history:

Received 4 March 2008

Received in revised form 5 June 2008

Accepted 10 July 2008

Keywords:

Wetting balance

Spreading

Soldering

ABSTRACT

Wetting balance tests of copper sheets submerged in tin solder baths were carried out in a completely automatic wetting balance. Wetting curves were examined for three different values of sheet thickness and four different solder bath temperatures. Most of the wetting curves showed a distorted shape relative to that of a standard curve, preventing calculation of important wetting parameters, such as the wetting rate and the wetting force. The wetting tests showed that the distortion increased for a thicker sheet thickness and a lower solder bath temperature, being the result of solder bath solidification around the submerged sheet substrate.

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1. Introduction

The good quality of several manufactured components frequently depends on solid–liquid interactions existing during processing. The spread of a liquid on a solid surface and the final wetting of the solid underlie several materials processing techniques. In metal–ceramic joining, Pask (1987) has presented an overview about how interfacial reactions and liquid metal spreading on solid ceramic substrates affect the quality of the joints. The importance of the wettability of steel wires by molten Zn and Sn during hot-dip coating of steel was shown by Shawki and Hanna (1980). Dautzat et al. (1992) have pointed out that the reaction between steel and molten Zn in the production of galvanized steels can be optimized by controlling the wettability of the solid steel substrate. Solomon et al. (2003) developed a special wetting balance to study the wetting of a Ni based alloy during brazing at temperatures as high as 1225 °C. Lee et al. (2005) also used a wetting balance to study the wetting behavior during the soldering process. In this process, used by the electronic industry, conditions for liquid spreading and solid wetting hold the key to the quality of the joint between component terminations and support

plates in electronic assemblies. Wassink (1989) emphasized that good solderability implies good wetting, proposing a classification of wetting behaviors. Manko (2001) recognized that the formation of a contact between solder and base metal depends on wetting.

Kumar and Prabhu (2007) have reviewed several aspects of wetting and the techniques to measure it, such as the wetting balance test. The wetting balance is basically a sophisticated load cell that measures the force on a solid surface that is first immersed into a liquid bath and next withdrawn from it. As a result, the balance gives a curve of force versus time, called the wetting curve. The curve shape is directly related to the liquid spreading and the solid wetting, which are affected by the solid surface condition, the liquid bath temperature, the thermal demand of the solid, the flux, and the environment gas, as shown by Wassink (1989).

Using the wetting balance test, Park et al. (1999) studied the wetting force on copper plates during withdrawal from Sn–Pb and Sn–Ag solder baths. Yu et al. (2000) examined the effects of several types of fluxes on the wetting curve, from which important wetting parameters were extracted. These authors searched for adequate fluxes to be used with lead-free solder

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doi:10.1016/j.jmatprotec.2008.07.015

alloys. Takemoto and Miyazaki (2001) analyzed the wettability of Sn–Ag and Sn–Zn lead-free solder alloys using the wetting balance test, measuring some wetting parameters, such as the wetting time, and the wetting force. From the wetting time obtained in tests carried out at different temperatures, they calculated an apparent activation energy for the wetting process and concluded that, in some cases, sequences of solder solidification and remelting around the sample controlled the spreading kinetics. No wetting curves or more details about this cyclic phenomenon were provided, however. Sattiraju et al. (2002) studied the wetting behavior of many lead-free solder bath alloys, namely Sn–3.4%Ag–4.8%Bi, Sn–4.0%Ag–0.5%Cu, Sn–3.5%Ag, and Sn–0.7%Cu, using the wetting balance test, from which the wetting force and wetting time were extracted. Cheng and Lin (2002) concluded from wetting balance curves that the wettability of a Sn–8.55%Zn–1%Ag solder alloy was improved by the addition of Al. Liu and Hutt (2006) used the wetting balance test to show the effect of the residual oxygen in the atmosphere on the wetting behavior of copper substrates. All of these researchers used the wetting balance test as a tool to investigate the kinetics of the spreading and wetting phenomena in several alloy systems employed in soldering processes. Han et al. (2002) modeled the wetting process that occurs in the wetting balance using computational fluid dynamics techniques and compared the model and experimental results using silicon oil.

To understand the temperature effect on the soldering process, ten Duis (1971) carried out a series of wetting balance tests. Copper sheets of 0.02 and 0.3 mm thickness were submerged into a solder bath of Sn–40%(wt.)Pb held at different temperatures. Increasing the sheet thickness resulted in less uniform wetting, and decreasing the bath temperature decreased the wetting rate. The author suggested that the latter effect was a result of several factors: the reduction of the flux efficiency, the decrease in the liquid viscosity, and the solidification of a portion of the solder bath at initial contact with the solid. Nevertheless, no evidence was provided to support those suggestions. Moreover, the force and time scales of the wetting curves were unclear and the curves were discussed only qualitatively, i.e., no quantitative characteristic parameters were obtained from them.

More recently, Chang et al. (2003) and Wang et al. (2006) have observed a decrease in the wetting time with an increase in temperature in the wetting balance tests of numerous substrates and solder alloys. Again, this temperature effect on the wetting behavior was neither discussed nor investigated.

After proposing some quantitative wetting parameters, Jellison et al. (1976) studied the effect of different copper substrates and types of solder baths on the wetting curves. A comparison between the measured wetting curves and a standard curve indicated a shape distortion, which for plain substrates was less pronounced than that for thick-film metallized substrates. Moreover, the measured force given by the wetting curves reached the maximum wetting force (F_w) earlier for plain substrates. The different levels of distortion and times to reach F_w were attributed to different heat transfer rates between solder bath and each type of substrate.

The main objective of the present work is to investigate the effects of the substrate sheet thickness and the bath temperature on the wetting curve shape, and on some of the wetting

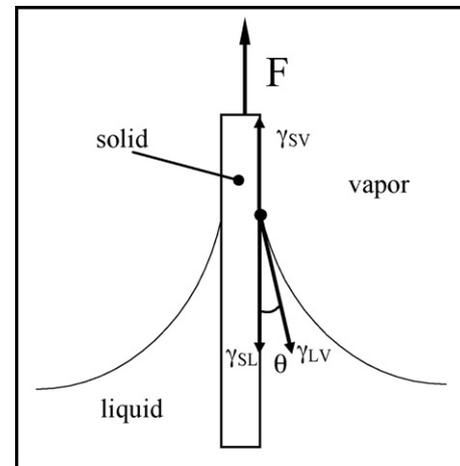


Fig. 1 – Measured force (F), contact angle (θ), and surface tension at the solid–liquid (γ_{sl}), solid–vapor (γ_{sv}), and liquid–vapor (γ_{lv}) interfaces in the wetting balance test.

parameters extracted from it. In order to obtain the wetting curves, several wetting balance tests are carried out for copper sheets immersed in tin solder baths. Conditions for wetting balance tests resulting in wetting curves without distortions are finally given.

2. The wetting balance curve

The wetting balance curve displays the vertical component of the force (F) applied by the wetting balance load cell on a solid sample (substrate) immersed into a liquid bath (solder), as shown in Fig. 1 (Wassink, 1989). The force measured by the wetting balance, F , can be related to the buoyancy force and the meniscus force, since the sample weight is compensated electronically at the beginning of the test. Therefore, Earle (1945), ten Duis (1971), and Jellison et al. (1976) have written the following equation:

$$F = P\gamma_{lv} \cos \theta - (v\rho g) \quad (1)$$

or alternatively

$$\gamma_{lv} \cos \theta = \frac{F + (v\rho g)}{P} \quad (2)$$

where γ_{lv} is the liquid–vapor surface tension; θ is the instantaneous contact angle shown in Fig. 1; P is the liquid meniscus perimeter around the solid sample; v is the volume of the partially immersed sample; ρ is the liquid density; and g is the acceleration of gravity. As explained by Orr et al. (1977), the first and second terms on the right hand side of Eq. (1) are the meniscus force and the buoyancy force, respectively.

A standard wetting curve is defined in the present work as a curve without distortions from which representative wetting parameters can be extracted. A representative wetting parameter should characterize the solid wetting or the kinetics of liquid spreading without interference of undesired effects. The following important points in the curve and some related wetting parameters are indicated in the schematic standard

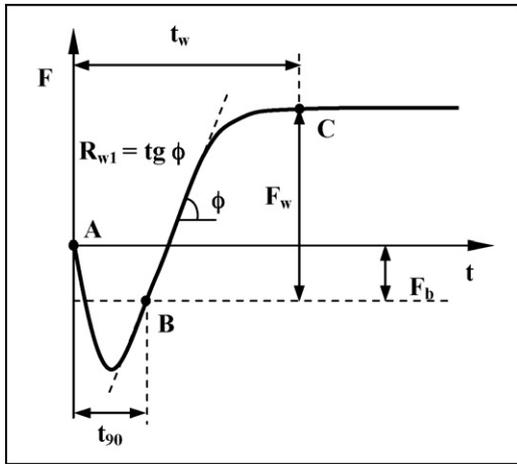


Fig. 2 – Schematic standard wetting curve. (A) Immersion; (B) point of 90° contact angle; (C) point of maximum wetting force; t_{90} : time to reach 90° contact angle; F_w : maximum wetting force; t_w : time to reach the maximum wetting force; R_{w1} : wetting rate, i.e., slope of the initial linear portion of the BC curve segment.

wetting curve shown in Fig. 2:

- point A indicates the first contact between the substrate and the solder bath;
- point B indicates the moment when the contact angle $\theta = 90^\circ$, and t_{90} is the time elapsed until this moment;
- F_b is the buoyancy force on the immersed sample ($v\rho g$);
- point C indicates the moment when the liquid spreading ends and the force F_w , defined as the maximum force relative to F_b , is reached;
- t_w is the time to reach the final wetting force, F_w ;
- R_{w1} is the wetting rate, i.e., the slope of the initial linear portion of the BC segment.

The parameters t_{90} , t_w , and R_{w1} are associated with the kinetics of the liquid spreading, whereas F_w is mainly associated with the solid wetting and might not be affected by the kinetics of the spreading process. Chang et al. (2003) have shown that t_w , and F_w are strong functions of both solders and substrates and the interfacial reactions between them.

3. Experimental procedure

A series of wetting balance tests of copper sheets in tin solder baths were carried out at four different temperatures, specifically 240, 250, 260, and 280 °C, with three different values of sheet thickness, namely 0.5, 1.0, and 1.5 mm. Each experimental condition was repeated three times to verify the reproducibility of the test and to improve the accuracy of the measured wetting parameters.

The substrate sheets were made of electrolytic copper and the solder bath was made of electrolytic tin. Before each balance test, the sheets went through a series of preconditioning steps: (1) ultrasonic cleaning in a solution of deionized water and detergent; (2) ultrasonic cleaning in alcohol; (3) cleaning

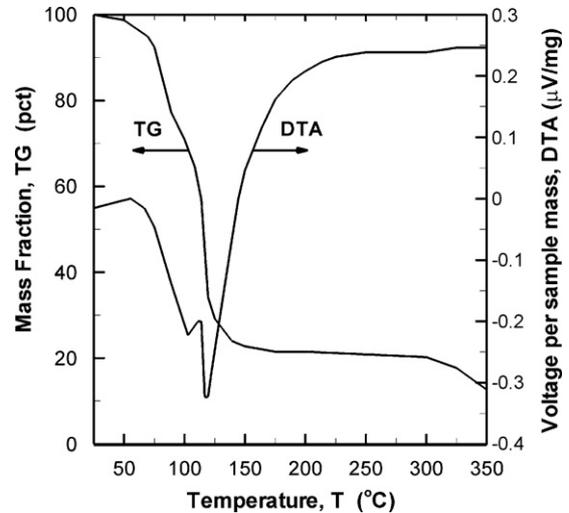


Fig. 3 – Ratio of instantaneous flux sample mass to initial mass (mass fraction), and differential thermocouple voltage per sample weight as a function of temperature.

in a solution of nitric acid; (4) rinsing with water, and (5) drying in air. Finally, immediately before the balance test, a rosin medium activated flux (ACTIEC2 – Trademark of Multicore Solders) was applied on the sheet surface.

To investigate the flux effect on the wetting curves, a flux sample was tested in a thermogravimetric balance (TG) with simultaneous differential thermal analysis (DTA). During this test, the sample was heated from 20 to 400 °C at a constant rate of 0.17 °C/s. The ratio of the instantaneous sample weight to the initial weight, and the differential thermocouple response per sample weight as a function of temperature are given in Fig. 3.

Each wetting balance test was performed in an automatic wetting balance called Must System II (Trademark of Multicore Solders) and consisted of the following steps: (1) the sheet substrate was preconditioned and connected to the balance load cell above the solder bath; (2) the solder bath temperature was measured at the approximate location at which the substrate would be immersed, and the bath surface was skimmed to remove the dross, taking about 30 s; (3) the solder bath was automatically raised towards the substrate at a velocity of 25 mm/s until 10 mm of the substrate had been immersed; (4) after the substrate had come in contact with the solder bath, the load cell registered the force during 30 s, called the immersion time; and (5) a curve of the force versus time, i.e., the wetting curve, was finally plotted. Table 1 shows the operation conditions for the wetting balance tests. More details of each test conditions and procedures can be found elsewhere (Martorano, 2001).

4. Results and discussion

The wetting curves measured in the present work are given in Figs. 4–6. The wetting parameters calculated from these curves should be representative of the kinetics of the liquid spreading and the solid wetting. Nevertheless, when the curve

Table 1 – Wetting balance test conditions

Test variable	Condition
Substrate immersion speed (mm/s)	25
Substrate immersion time (s)	30
Substrate immersion depth (mm)	10
Substrate width (mm)	15
Substrate thickness (mm)	0.5; 1.0; 1.5
Substrate immersed mass (10^{-3} kg)	0.67; 1.3; 2.0
Solder bath temperature ($^{\circ}$ C)	240; 250; 260; 280
Solder bath mass (kg)	0.88
Flux type	Medium activated (Multicore/Actiec 2)

is distorted, as observed in some cases, the wetting parameters cannot convey the desired information. Except for the wetting curve of Fig. 4(d), all curves presented in Fig. 4 display a long plateau or a series of short plateaus of increasingly

large force. The plateaus always occur during liquid spreading, i.e., before the stable maximum force (F_w) is reached, and they represent a distortion of the standard wetting curve given by Fig. 2. As will be discussed later, those plateaus are a result of processes not directly associated with the interfacial phenomena of liquid spreading, but they strongly affect the wetting parameters extracted from the curves. Therefore, they should be eliminated.

An increase in the solder bath temperature and a decrease in the substrate sheet thickness eliminated the plateaus in some of the curves and decreased the wetting time. Chang et al. (2003) and Wang et al. (2006) have also observed a decrease in the wetting time for an increase in temperature for copper substrates immersed in tin melts. In the experiments with sheets of 0.5 mm thickness, an increase in the bath temperature from 240 to 280 $^{\circ}$ C removed all plateaus, as seen in Fig. 4(a–d). Since the curve in Fig. 4(d) had the standard shape, its associated wetting parameters were calculated and given in Table 2. With sheets of 1.0 mm, however, the same temperature increase did not completely eliminate the plateaus, as shown in Fig. 5(a) and (b). Some wetting delay is still observed in Fig. 5(b). Moreover, comparing Figs. 4(a), 5(a), and 6(a) indi-

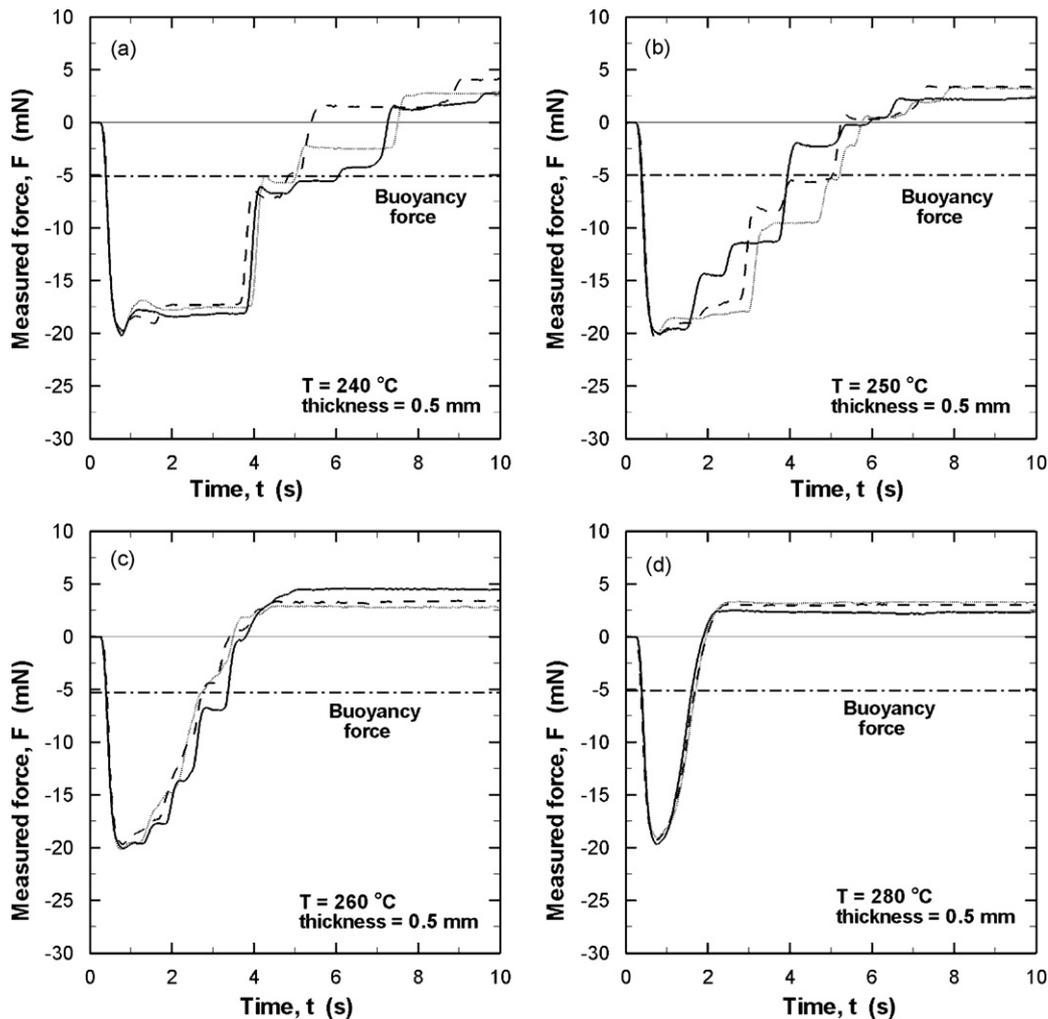


Fig. 4 – Wetting curves (force vs. time) from three repetitions of wetting balance tests of copper sheets of 0.5 mm thickness in tin solder baths at different temperatures: (a) 240 $^{\circ}$ C; (b) 250 $^{\circ}$ C; (c) 260 $^{\circ}$ C; and (d) 280 $^{\circ}$ C.

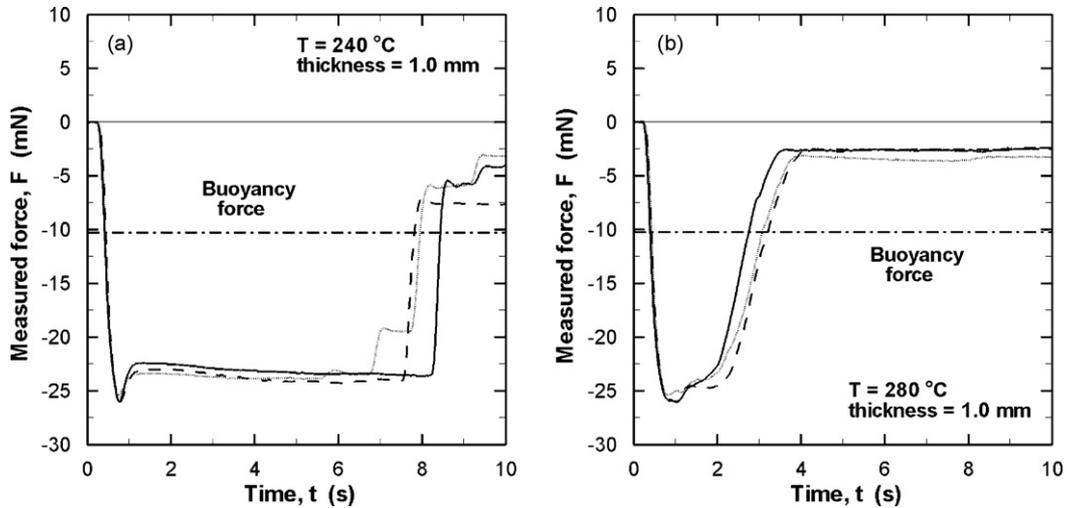


Fig. 5 – Wetting curves (force vs. time) from three repetitions of wetting balance tests of copper sheets of 1.0 mm thickness in tin solder baths at two different temperatures: (a) 240 °C and (b) 280 °C.

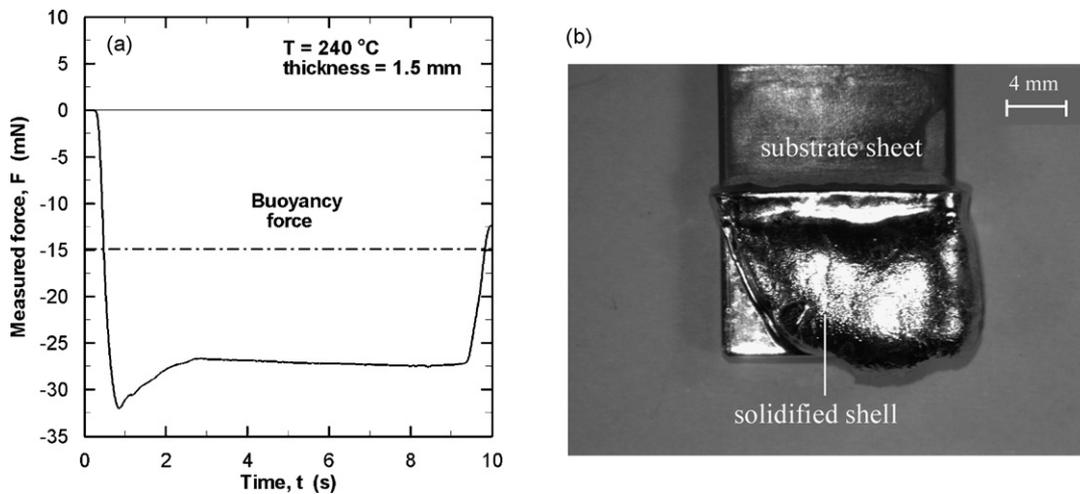


Fig. 6 – Wetting balance test of a copper sheet of 1.5 mm thickness in a solder bath at the temperature of 240 °C: (a) wetting curve (force vs. time); (b) solidified shell on a copper sheet pulled out of the solder bath during the wetting delay period.

icates an increase in the wetting delay for an increase in the sheet thickness from 0.5 to 1.5 mm at the temperature of 240 °C.

Shawki and Hanna (1980) and Wassink (1989) argue that the wetting delay at the beginning of the liquid spreading is attributed to the time for the substrate temperature to reach the bath temperature after immersion. As shown by Wassink (1989), a decrease in the temperature caused an increase in

the time for the rosin flux solvent evaporation and for the flux activation, which suggests that the temperature effect on the curves might be the result of an indirect effect of temperature on the flux.

An attempt was made to estimate the effect of the flux solvent evaporation on the wetting delay observed in the present work curves. The evolution of flux sample weight shown in Fig. 3 indicates that the solvent evaporation occurs at approximately 120 °C. This temperature was confirmed by the differential thermal analysis curve, which shows an endothermic reaction at the same temperature. If the wetting delay is related to the time for solvent evaporation, it must be inversely proportional to the heat flux absorbed in the endothermic process. This heat flux is assumed to be proportional to the difference between solvent and solder bath temperature. This difference is 120 °C (240–120 °C) for the bath at 240 °C, and 160 °C (280–120 °C) for the bath at 280 °C. Therefore, an increase in bath temperature from 240 to 280 °C would cause a heat flux increase of 33%, representing a 33% decrease

Table 2 – Wetting parameters and 95% confidence intervals calculated from the wetting curves shown in Fig. 4(d)

Wetting parameter	
t_{90} (s)	1.7 ± 0.2
t_w (s)	2.4 ± 0.2
R_{W1} (mN/s)	26 ± 2
F_w (mN)	2.9 ± 0.9

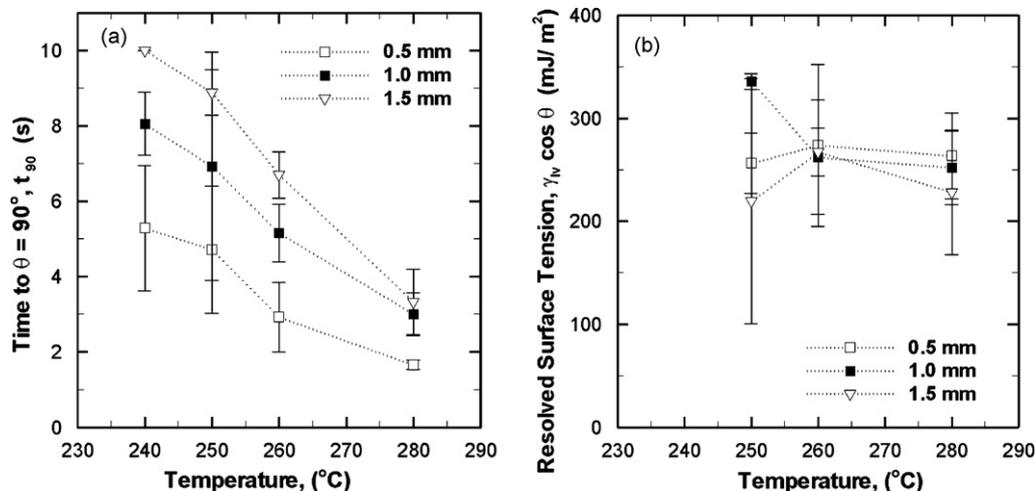


Fig. 7 – (a) Time t_{90} and (b) liquid–vapor surface tension resolved in the vertical direction as a function of temperature for each substrate sheet thickness; error bars indicate 95% confidence intervals.

in the evaporation time. For the sheet of 0.5 mm thickness, this time decrease should correspond to a change in the wetting delay from 3 s, for a solder bath at 240 °C (Fig. 4(a)), to 2 s, for the bath at 280 °C (Fig. 4(d)). Nonetheless, the wetting delay completely disappeared in the bath at 280 °C, indicating that solvent evaporation plays a minor role in the wetting delay.

A wetting balance test was interrupted by pulling the copper substrate sheet out of the solder bath in the middle of the wetting delay period. To enhance the wetting delay effect, the sheet thickness of 1.5 mm and the bath temperature of 240 °C were adopted, which resulted in the wetting curve shown by Fig. 6(a). After examining the sample, it was clear that solidification of the solder bath occurred around the substrate, as shown by Fig. 6(b). The same procedure was carried out for the substrate corresponding to the wetting curve of Fig. 4(d). Now, without the wetting delay, the substrate was pulled out of the bath before liquid spreading, i.e., approximately at the moment of the lowest force indicated by the wetting curve. No solidification was observed around the substrate in this case. Consequently, the wetting delay was caused by the solidification of the solder bath around the copper sheet substrate. Although Budrys and Brick (1971) and ten Duis (1971) suggested this mechanism to explain the wetting delay, no experimental evidence was ever given to confirm it.

The wetting delay (long plateau) and short plateaus observed in the wetting curves were caused by solidification of a solder shell around the copper sheet substrate. The solid substrate extracts heat from the surrounding liquid causing solidification of a shell, which eventually remelts. This effect is enhanced for substrates of relatively high thermal conductivity, such as the copper sheets, because the substrate surface temperature increases more slowly, keeping the heat flux high for a longer time. The short plateaus are the result of a sequence of solidification and remelting steps as the liquid spreads on the solid substrate and gets in contact with a clear and colder surface.

The plateaus caused by the solidification and remelting cycles directly affected the kinetics of spreading, measured

by t_{90} , as shown in Fig. 7(a). The time for liquid spreading decreased, and consequently t_{90} also decreased for either a decrease in sheet thickness or an increase in bath temperature, as observed by other authors (Chang et al., 2003; Wang et al., 2006). As the bath temperature increased, the t_{90} corresponding to all sheets of different thickness seemed to converge to the same value of about 3 s, which indicated that solidification and remelting no longer played an important role in the spreading kinetics. Moreover, at higher temperatures the substrate sheet thickness was no longer important in the spreading process, resulting in the same t_{90} .

The liquid–vapor surface tension resolved in the vertical direction, $\gamma_{lv} \cos \theta$, as given by Eq. (2), was calculated from the wetting curves and is shown in Fig. 7(b). The effect of temperature and substrate sheet thickness on $\gamma_{lv} \cos \theta$ seems to be small and no clear tendency is observed. A larger scatter of data points, however, was observed for the lowest temperature or for the thickest substrate sheet. The effect was attributed to the plateaus observed during the liquid spreading. In other words, solidification and remelting during spreading seemed to affect not only the spreading kinetics, but also the precision of wetting parameters measured even after the system had reached equilibrium.

In the present work, for a substrate thickness of 0.5 mm, a solder bath temperature of 280 °C, representing a superheat of 48 °C above the melting point of pure tin, was required to yield wetting curves without distortions. A superheat of 28 °C (i.e., a solder bath temperature of 260 °C) would not be high enough to avoid the distortions caused by solidification–remelting cycles of a solid shell around the substrate. Chang et al. (2003) adopted superheats of 8 and 18 °C for copper substrates immersed into solder baths or pure tin, but the wetting curves were not given. The wetting curve presented by Wang et al. (2006) for pure copper substrates immersed on a Sn–0.7(%wt)Cu solder bath was not distorted for a superheat of 40 °C, which is approximately the superheat recommended in the present work. For a superheat of 30 °C, no wetting curves were presented by these authors (Wang et al., 2006).

5. Conclusions

Under certain test conditions, wetting curves obtained by the wetting balance tests of copper sheet substrates in tin solder baths might show some distortion relative to the expected standard wetting curve. For thicker sheet substrates and lower bath temperatures, long and short plateaus are observed in the wetting curves, causing a delay in the wetting time. These effects are the result of solidification and remelting of a solid shell around the substrate sheets and seem to be unrelated to the flux solvent evaporation. As the temperature increases, the effects fade away and the spreading kinetics is independent of the substrate sheet thickness.

Accurate parameters representing the liquid spreading and the solid wetting can only be extracted from the wetting curves if the effects of solder solidification and remelting are absent, i.e., if the wetting curves are undistorted. Consequently, some previous experiments should be conducted to find an adequate solder temperature for a specific substrate material and thickness. For copper sheet substrates of 0.5 mm thickness, a superheat of 48 °C above the melting point of the solder bath was required to yield undistorted wetting curves, while superheats smaller than or equal to 28 °C were not high enough.

Acknowledgements

The authors wish to thank FAPESP (Fundação de Amparo à Pesquisa do Estado de São Paulo) for the support to this work under grants 95/9113-2, 96/04242-1, and 03/08576-7.

REFERENCES

- Budrys, R.S., Brick, R.M., 1971. Variables affecting wetting of tinplate by Sn–Pb solders. *Metall. Trans.* 2, 103–110.
- Chang, H.Y., Chen, S.W., Wong, D.S.H., Hsu, H.F., 2003. Determination of reactive wetting properties of Sn, Sn–Cu, Sn–Ag, and Sn–Pb alloys using a wetting balance technique. *J. Mater. Res.* 18, 1420–1428.
- Cheng, S.C., Lin, K.L., 2002. The thermal property of lead-free Sn–8.55Zn–1Ag–XAl solder alloys and their wetting interaction with Cu. *J. Electron. Mater.* 31, 940–945.
- Dauzat, M., Moreau, T., Roch, M.J., Roualdes, J., 1992. Wettability—a new approach of galvanizing. *Rev. Metall. -Paris* 89, 896–897.
- Earle, L.G., 1945. A quantitative study of soft soldering by means of the Kollagraph. *J. I. Met.* 71, 45–72.
- Han, J.W., Lee, H.G., Park, J.Y., 2002. Numerical simulation of dynamic wetting behavior in the wetting balance method. *Mater. Trans.* 43, 1816–1820.
- Jellison, J.L., Johnson, D.R., Hosking, F.M., 1976. Statistical interpretation of meniscograph solderability tests. *IEEE T. Parts Hyb. Pac.* 12, 126–133.
- Kumar, G., Prabhu, K.N., 2007. Review of non-reactive and reactive wetting of liquids on surfaces. *Adv. Colloid. Interface* 133, 61–89.
- Lee, T.K., Zhang, S., Wong, C.C., Tan, A.C., 2005. Instantaneous fluxless bonding of Au with Pb–Sn solder in ambient atmosphere. *J. Appl. Phys.* 98, 0349041–0349047.
- Liu, C.Q., Hutt, D.A., 2006. Fluxless soldering of copper substrates using self-assembled monolayers for preservation. *IEEE T. Compon. Pack. T.* 29, 512–521.
- Manko, H.H., 2001. *Solders and Soldering: Materials, Design, Production, and Analysis for Reliable Bonding*, fourth ed. McGraw-Hill, New York.
- Martorano, K.M., 2001. *Wetting and Spreading of Liquid Tin and 60%Sn–40%Pb Alloy on Sheets of Copper and Copper–Tin Alloys*, Thesis (in Portuguese), University of São Paulo, São Paulo.
- Orr, F.M., Scriven, L.E., Chu, T.Y., 1977. Menisci around plates and pins dipped in liquid—interpretation of wilhelmy plate and solderability measurements. *J. Colloid. Interf. Sci.* 60, 402–405.
- Park, J.Y., Kang, C.S., Jung, J.P., 1999. The analysis of the withdrawal force curve of the wetting curve using 63Sn–37Pb and 96.5Sn–3.5Ag eutectic solders. *J. Electron. Mater.* 28, 1256–1262.
- Pask, J.A., 1987. From technology to the science of glass metal and ceramic metal sealing. *Am. Ceram. Soc. Bull.* 66, 1587–1592.
- Sattiraju, S.V., Dang, B., Johnson, R.W., Li, Y.L., Smith, J.S., Bozack, M.J., 2002. Wetting characteristics of Pb-free solder alloys and PWB finishes. *IEEE T. Electron. Pa. M.* 25, 168–184.
- Shawki, S., Hanna, F., 1980. Wetting characteristics of steel by molten metals. *T. Iron Steel I. Jpn.* 20, 73–79.
- Solomon, H.D., Delair, R.E., Thyssen, J., 2003. The high-temperature wetting balance and the influence of grit blasting on brazing of IN718. *Weld. J.* 82, 278s–287s.
- Takemoto, T., Miyazaki, M., 2001. Effect of excess temperature above liquidus of lead-free solders on wetting time in a wetting balance test. *Mater. Trans.* 42, 745–750.
- ten Duis, J.A., 1971. Soldering and Reliability. In: *International Electronics Packaging and Production Conference, Industrial Scientific Conference Management Inc, Brighton*, pp. 56–75.
- Wang, H.Q., Gao, F., Ma, X., Qian, Y.Y., 2006. Reactive wetting of solders on Cu and Cu₆Sn₅/Cu₃Sn/Cu substrates using wetting balance. *Scripta Mater.* 55, 823–826.
- Wassink, R.J.K., 1989. *Soldering in Electronics: a Comprehensive Treatise on Soldering Technology for Surface Mounting and Through-Hole Techniques*, second ed. Electrochemical Publications, Ayr, Scotland.
- Yu, S.P., Liao, C.L., Hon, M.H., Wang, M.C., 2000. The effects of flux on the wetting characteristics of near-eutectic Sn–Zn–In solder on Cu substrate. *J. Mater. Sci.* 35, 4217–4224.