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Physical Meaning of Wetting Curve Traced by Meniscograph Wettability Tester†

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Abstract

The wetting curve traced by a meniscograph wettability tester was analized physically by applying the equation of one-dimensional heat conduction. If the oxide film on a specimen is removed by surface preparation, the wetting curve of the specimen is the "locus of 456K (183°C)". Here, 456K is the melting point of a used solder. Therefore, the wetting rate or the wetting time are dependent only on the heat conductivity of the used specimen.

KEY WORDS: (Solderability) (Wettability) (Wetting Rate) (Wetting Time) (Electronics Parts)

1. Introduction

Various wettability testing methods are used in soldering. In these methods, the meniscograph method is a most suitable method, because it is possible to investigate directly the changes in wetting force as a function of time within a short time. However, the wetting (the meniscograph force-time trace) curve is not enough analized physically yet. At present, therefore, as a convenient measure of wettability, three measures such as reference wetting force$^{1)}$, wetting time$^{2-4)}$ and wetting rate$^{5-6)}$ etc. are used by comparing these measures with several new ones. Nagasawa$^{7)}$ analized the physical meaning of the wetting curve based on the assumption that the temperature of the specimen is equal to the temperature of solder bath. In practice, however, the temperature of the specimen is a room temperature or 353∼373K (80∼100°C) at most in the wave soldering processes in electronics part industries.

This paper describes the physical meaning of the wetting curve, especially, the physical meaning of the steep part that was defined as the wetting rate or wetting time by the earlier investigators, when the specimen is not preheated and the oxide film on the specimen is removed well enough by surface preparation and the used flux. As an analizing method, the equation of one-dimensional heat conduction was used, because, in this testing method, the specimen is a thin plate and the heat is given from the bottom edge to the upper edge of the specimen by the free surface or the meniscus surface (i.e. negative and positive) of the molten solder. Therefore, the temperature of heat source used in the calculation is the surface temperature of the molten solder.

2. Materials and Experimental Procedures

Copper strip of the size 50(l) x 5(w) x 0.5(t) mm was used as the specimen. Surface preparation was made by emery polishing No.600 followed by a ultrasonic cleaning in aceton and then air dried. The used flux is 35 mass% rosin alcohol solution plus DMA HCl and the concentration of Cl is 0.2 mass%. The specimen after surface preparation was immersed in the flux solution at a room temperature for 5 seconds and then was secured in the holder by the clamping screw of a meniscograph tester. The used solder is eutectic Pb-Sn alloy and the temperature at the position of 4 mm below from the surface of molten solder was adjusted to each predetermined temperature and the surface temperature was measured by a thermocupls with a porcelain tube. The conditions that the specimen was dipped to the solder bath are as follows; ① the velocity, 4 mm/sec, ② the depth, 4 mm, and the

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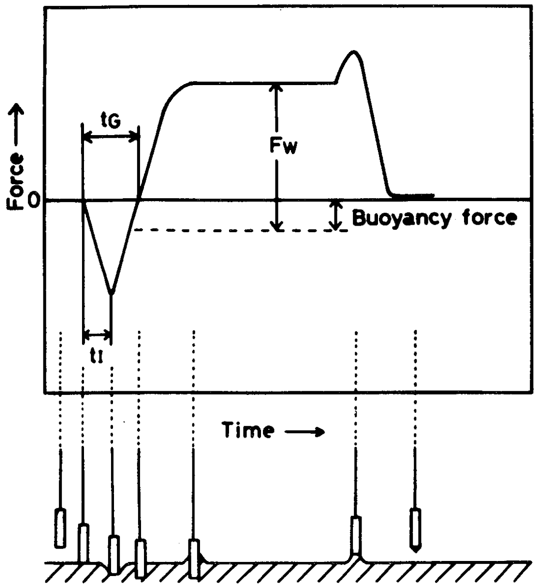

Fig. 1 Schematic of wetting curve and definition of t_I, t_G and F_W.

dipped specimen was drawn out from the solder bath after the holding time of 10 seconds.

Figure 1 shows the schematic of wetting curve, as well known. In Fig. 1, t_I is the time that the wetting of solder begins at the bottom edge of the specimen. t_G is the time that the apparent repulsion force acted on the specimen becomes to zero. F_W is the maximum wetting force at equilibrium. The wetting curve from time t_I to equilibrium will be analized below on the heat conduction of the specimen.

3. Results and Discussions

3.1 For pure copper specimen

Each full line in **Fig.** 2(a), (b), (c) and (d) is the typical measured wetting curve at each temperature. The temperature shown in each figure is the measured surface temperature of molten solder and, as mentioned already, the temperature at the depth 4 mm is shown in a parenthesis. The vertical axis represents the force (mN) acted on the specimen and the distance (x) with intervals 1 mm. This was defined as follows; namely, following meniscograph testing, the portion of each specimen which wetted with solder was measured with an optical comparator. The height was 6 mm, therefore, the wetting curve from time t_I to equilibrium was divided up equally six parts with intervals 1 mm. The distance, x, accordingly, means the meniscus rising height of solder at each time.

Now, the bottom edge of the specimen contacts the surface of molten solder and the heat transfers to the upper edge of the specimen. It is one-dimensional heat conduction and, as well known, the following equation was applied

$$T_x = (T_S - T_r)\ \{1 - \mathrm{erf}(\frac{x}{2\sqrt{kt}})\} + T_r \qquad (1)$$

where T_x is the temperature of the specimen at the position that the distance from heat source is x. T_S is the temperature of heat source, i.e., the surface temperature of molten solder. T_r is the temperature of specimen before dipping. This temperature was 313K (40°C), because the specimen was preheated by the radiation heat from the solder bath during the fluxed specimen is secured in the holder of the meniscograph tester. x is the distance from heat source. k (= $\lambda/\rho c$ = 1.142) is the thermal diffusivity and λ is the heat conductivity of copper, ρ is the density of copper, c is the specific heat of copper, t is the elapsed time from which the solder surface, i.e. heat source and the bottom edge of the specimen first make contact.

Mark (i), i.e. the open circules in Fig. 2(a) are the calculated values of the required time that the temperature at each distance of the specimen reaches 456K (183°C) of the melting point of the used solder, when the solder surface of 486K contacts the bottom edge of the specimen, i.e. the position of heat source is $x = 0$ and is fixed. In the same way, mark (ii), i.e. the solid circules in Fig. 2(a) are the calculated time values that the temperature reaches 456K at each distance of the specimen, when the heat source exists $x = 2.7$ mm and is fixed, i.e. the solder surface rises from the bottom edge of the specimen to this distance, and in this case the force, F, is zero. Both the plotted marks, as seen in mark (iii) of Fig. 2(a), were superposed on the full line, i.e. on the measured wetting curve, based on the elapsed time. Fig. 2(b), (c) and (d) are same for the calculation procedures, but, the temperatures of heat source are 499K, 512K and 526K, respectively. From these results, it was discovered that the wetting curve which corresponds to the wetting rate defined by earlier investigators is the "locus of 456K (183°C)". When these figures are seen in detail, the calculated values shift slightly to a shorter time side than the measured full line. This is considered that the temperature of heat source used in the calculation, for example, 486K in Fig. 2(a) is higher than the surface temperature of the molten solder in practice. Namely, the measured surface temperature of molten solder was 486K, but when the specimen contacted the molten surface, the heat is transmitted to the specimen, reversely, the surface temperature instantaneously decreases to 456K or below. The rough estimation of this temperature is possible as follows; for example, the surface temperature = 486K, the specimen temperature before dipping = 313K, accordingly, 486 + 313/2 ≑ 400K (127°C). This value is lower than the

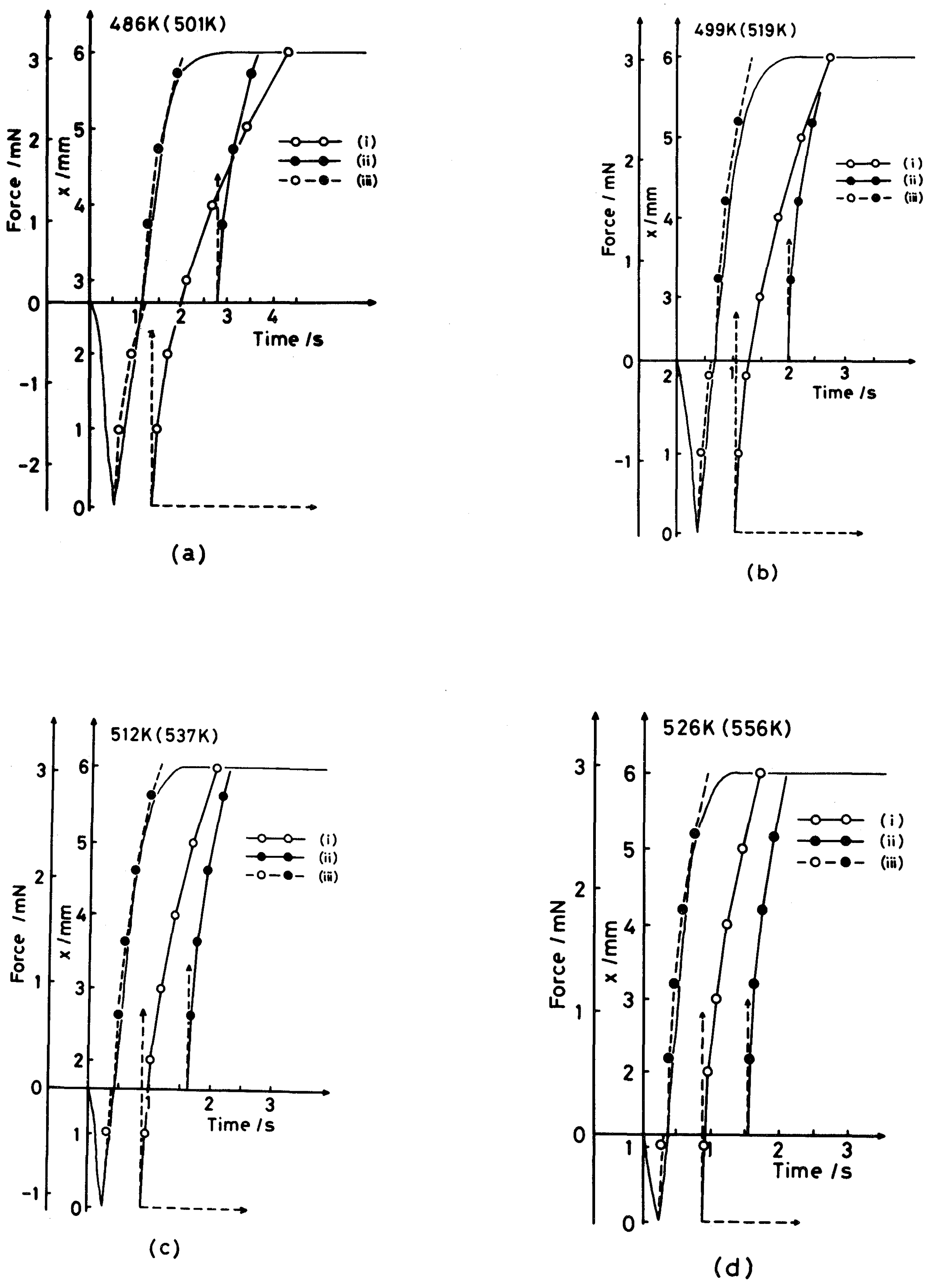

Fig. 2 Analysis of wetting curve by equation of one-dimensional heat conduction. Each wetting curve was traced at each molten surface temperature 486K(a), 499K(b), 512K(c) and 526K(d).

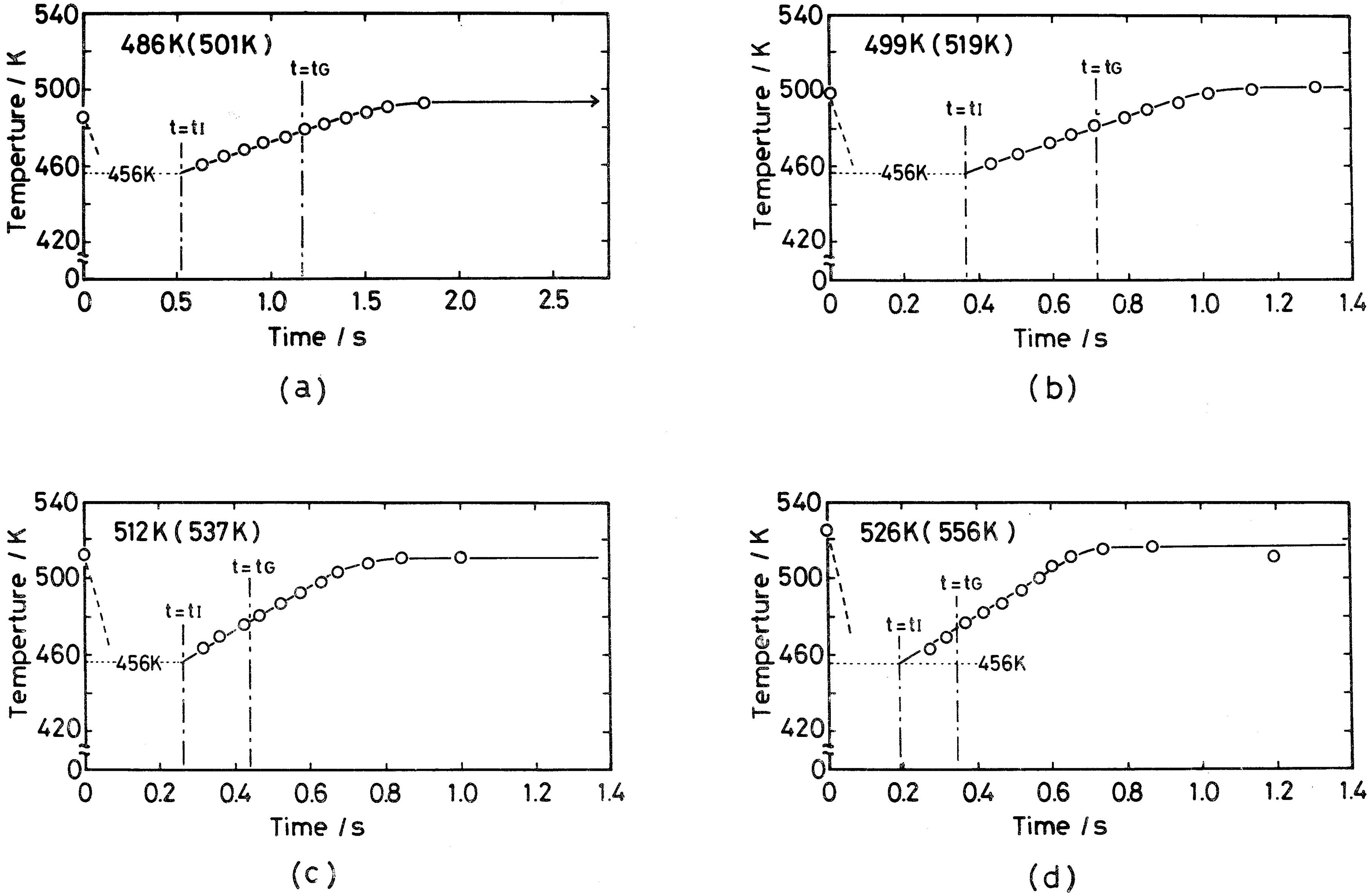

Fig. 3 Time dependence of bottom edge temperature of pure copper specimen. Temperature was calculated by using eq.(1) and measured wetting curve shown in each figure of Fig. 2.

melting point of the used solder (183°C). If the molten surface is solidified by this temperature decreasing, the "locus of 456K" will be justified, because the solidified surface initially remelts at 456K and wetting occurs at the bottom edge of the specimen. Therefore, the temperature of the front of meniscus by wetting is 456K and also, during the meniscus rising from time t_I to equilibrium, the temperature of the front of meniscus is constant, i.e. the wetting force is constant and the magnitude is the sum of 3 mN as shown in each figure of Fig. 2 and 0.84 mN of the buoyancy force of the specimen (See F_W in Fig. 1).

As known from the discussion mentioned above, the bottom edge temperature of the specimen changes with elapsing of time. **Fig. 3** shows the time dependence of the bottom edge temperature of the specimen calculated by using the measured wetting curve shown in Fig. 2(a), (b), (c) and (d), respectively. The temperatures were calculated by using eq.(1) as follows;

① T_S is the temperature of the bottom edge of the specimen and is unknown.

② T_x is 456K, i.e. this is the temperature at each distance, x, on the specimen.

③ x is the distance that the meniscus of solder rised at each time, for example, as shown in Fig. 2, x is zero mm at time t_I and is 6 mm at equilibrium. This interval was divided up equally twelve parts, i.e. $x = 0$, 0.5, 1.0, 1.5, ..., 6.0 mm. Of course, the temperature of the bottom edge at $x = 0$ can not to calculate as known from eq.(1). Then, this temperature is discussed by using an extrapolation method as mentioned later.

④ t is the required time that the meniscus of solder rises to each distance, x,. This value was obtained graphically by using the measured wetting curves, i.e. the full lines shown in Fig. 2(a), (b), (c) and (d). As seen in Fig. 3(a), (b), (c) and (d), the bottom edge temperature increases with increasing of time and the final temperature is saturated. This saturated temperature value is about equal to the plotted temperature value on the vertical axis. This plotted value is the measured surface temperature of molten solder, i.e. when the bottom edge contacts the molten surface, the bottom edge temperature must be the molten surface temperature. Therefore, as the bottom edge temperature at $t = 0$ second, the measured molten surface temperature was plotted on the vertical axis. This bottom edge temperature, as mentioned above, instantaneously decreases. In each figure of Fig. 3, as an one-point broken line, time t_I and time t_G, which were measured graphically by using the measured wetting curve in each figure of Fig. 2, were plotted. The one-point broken line of time t_I intersects at 456K with the linear line that connects with each calculated bottom edge temperature of the specimen. From this result, it is emphasized that the wetting of molten solder at the bottom edge of the specimen begins at 456K and the wetting curve is the "locus of 456K". Furthermore, as mentioned above, the final value of the bottom edge temperature agrees with the measured surface temperature of molten solder. From this result, it is presumed that the temperature of the front of meniscus at equilibrium of wetting curve is lower than the surface temperature of molten solder. This may be justified by the following reason, i.e. the temperature of the surface adjacent to a copper strip must be lower than the temperature of the free surface of molten solder, because the heat radiation of copper is bigger than that of the air.

3.2 For copper alloy specimen

In general, the heat conductivity of copper alloy is less than that of pure copper. Then Cu-1.41 at% Ti alloy was used for the meniscograph testing method, to confirm the "locus of 456K" mentioned above. The thermal diffusivity of this alloy was $k = 0.616$ cm^2/sec against $k = 1.142$ cm^2/sec of pure copper. In the experiment, the size of the specimen, both the compositions of the used solder and the used flux, the dipping conditions etc. are the same as those of pure copper specimen mentioned above. In **Fig. 4** a full line is the typical measured wetting curve of this alloy, which was dipped in the molten surface temperature of 486K. Accordingly, this figure corresponds to Fig. 2(a) of pure copper specimen. In Fig. 4, the calculation procedures for each mark are entirely same as those mentioned in section 3.1, except that the position of heat

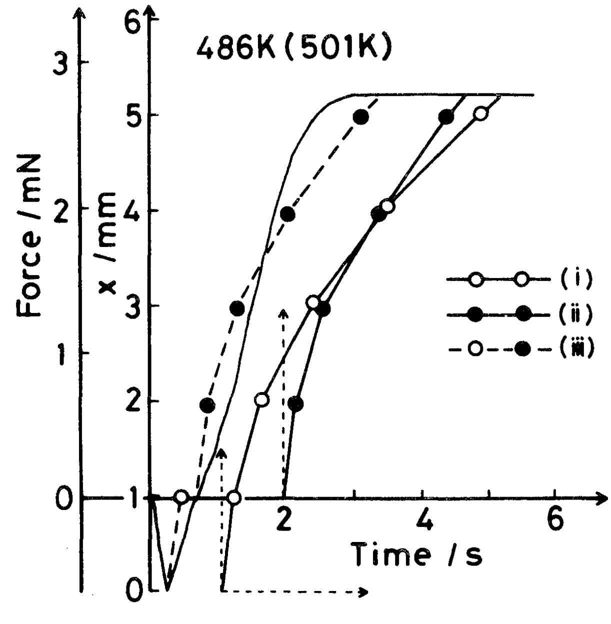

Fig. 4 Analysis of wetting curve of Cu-Ti alloy. Wetting curve was traced at molten surface temperature 486K.

source is $x = 1.0$ mm in the calculation of the solid circules and also the measured wetting curve was divided up equally five parts because the maximum wetting force is less than that of the pure copper specimen. As seen in Fig. 4, although an approximate agreement between the measured wetting curve and the calculated values is recognized, the "locus of 456K" will be applied also in the case of Fig. 4. **Fig. 5** shows the time dependence of the bottom edge temperature of the specimen calculated by using eq.(1) and the measured wetting curve shown in Fig. 4. The calculation procedures are same as the case of Fig. 3(a). A full line in Fig. 5 is the result of Fig. 3(a). By comparing this full line with the calculated values of Cu-1.41at%Ti alloy, it is evident that the slope of Cu-alloy is not shap for that of pure copper and this is attributed to the different thermal diffusivities of both specimens. In Fig. 5, the time t_I that was measured graphically from the measured wetting curve shown in Fig. 4 was plotted as an one-point broken line. This one-point broken line intersects at 456K with the linear line which connects with each calculated value. This result is as good as obtained in each figure of Fig. 3. But, as seen in Fig. 5, this point of intersection is a shorter time side than that of pure copper, i.e. that of the full line. This is attributed to that, when the Cu-Ti alloy of a low thermal diffusivity contacts to the molten surface, the heat loss of the molten surface is less than that of the molten surface which contacts to the pure copper of a high thermal diffusivity. From this consideration, it is derived that if a specimen is preheated at least to the melting point of a used solder, the time t_I becomes zero second and the effect of heat conduction is able to neglect.

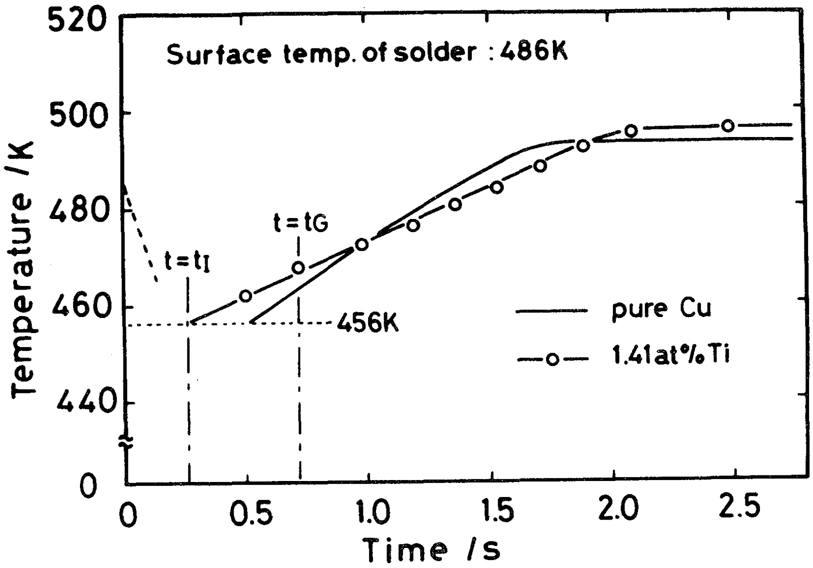

Fig. 5 Time dependence of bottom edge temperature of Cu-Ti alloy specimen. Calculation was made by using eq.(1) and measured wetting curve shown in Fig. 4.

4. Conclusions

The wetting curve traced by a meniscograph tester was analized physically by applying the equation of one-dimensional heat conduction. The results are sammarized as follows;

1) If the oxide film on the specimen was removed well enough, the wetting curve that was defined as wetting rate or wetting time by earlier investigators is the "locus of 456K (183°C)". Therefore, the wetting rate or wetting time are dependent only on the heat conductivity of the specimen. Here, 456K is the melting point of the solder used.
2) When the specimen contacts the molten surface of solder, the surface temperature instantaneously lowers remarkably, and the instantaneous solidification of solder surface occurs and again the solidified surface melts at 456K. At this time, the wetting of the solder begins at the bottom edge of specimen and the meniscus of solder rises on the specimen surface with the velocity that the temperature of each position on the specimen reaches to 456K. It is the "locus of 456K" and the wetting force during the rising is constant.

In our experiment, the eutectic Pb-Sn alloy of m.p. 456K was used. Therefore, as a general theory, it should be called as the "locus of melting point of a used solder". Moreover, when the oxide film on a specimen is not removed by flux until the surface temperature of molten solder recovers the melting point of the used solder, the physical analysis of the wetting curve will be published in next issue.

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