ANALYSIS OF PACKAGE CRACKING DURING REFLOW SOLDERING PROCESS

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Abstract

Surface mount packages are heated up above solder melting temperature during reflow soldering process. If the plastic encapsulant has absorbed moisture, package cracking may occur. In this study, an evaluation method of the package cracking is developed by means of moisture diffusion analysis of plastic and deformation and stress analysis of packages.

Introduction

Recently plastic IC packages have been changing from insertion types (Fig. 1(a)) to surface mounted types (Fig. 1(b)). Surface mounted devices (SMD) soldered directly onto lands on the surface of a printed circuit board (PCB) reduce the size, complexity and costs of PCBs and facilitate automation of PCB assembly [1]. Reflow soldering such as vapor phase (VP) soldering or infrared (IR) soldering is used for soldering SMDs onto PCBs. During the process, packages are heated up above solder melting temperature. If the plastic encapsulant has absorbed moisture, package cracking may occur during reflow soldering as shown in Fig. 2. Cracking must be prevented to guarantee the reliability of the mounted devices. Cracks are caused by vapor pressure generated inside the package causing excessive stress in the plastic [2]. The influence of package structure on package cracking has been investigated experimentally and rates of moisture absorption and desorption of packages have been measured [3].

A quantitative explanation of the mechanism of this phenomenon, however, has not been made, and a radical package design to overcome this problem is not available at present. The purpose of this study is to develop a method to explain the phenomenon quantitatively. In this study, a moisture diffusion analysis of the plastic and a deformation and stress analysis of packages were performed, and strength evaluation was made.

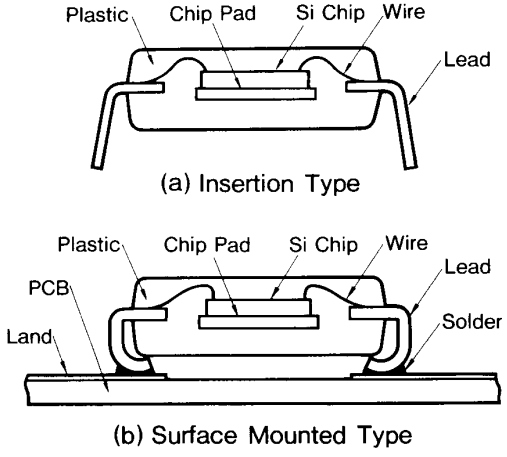

Fig. 1 Structure of IC Packages

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Analysis of Package Cracking Mechanism

Package cracking occurs as follows:

(1) Moisture absorption process : Atmospheric moisture dissolves and diffuses in the plastic encapsulant.
(2) Vaporization process : Moisture at the interface between the chip pad and the plastic is vaporized by heating during reflow soldering. The vapor pressure deforms the plastic below the chip pad and causes stress in the plastic. If the stress is excessive, package cracking occurs.

In this study, a moisture diffusion analysis in the plastic and deformation and stress analysis of the packages were performed.

An outline of the package during reflow soldering is shown in Fig. 3(a). Delamination of the plastic from the chip pad occurs. Plastic below the chip pad is deformed by vapor pressure generated in the space between the chip pad and the plastic. The plastic is modeled as shown in Fig. 3(b). Since the chip pad size is large enough compared to the thickness of the plastic, diffusion of the moisture can be considered to be only in the direction perpendicular to the chip pad. The space between the chip pad and the plastic is filled with vapor due to moisture in the plastic.

The mass content of the moisture in the plastic C is a function of distance from chip pad x and time t. This relation is described by the following diffusion equation from Fick's second law:

$$\frac{\partial C}{\partial t}=D\frac{\partial^2 C}{\partial x^2}, \qquad (1)$$

where D is diffusion coefficient of moisture in the plastic and assumed to be independent from moisture content. Initial and boundary conditions are:

Initial condition : $C(t=0)=C_0(x)$. (2)
Boundary conditions : $C(x=0)=pS$: (3)
$C(x=h)=\rho p_S S$: (4)

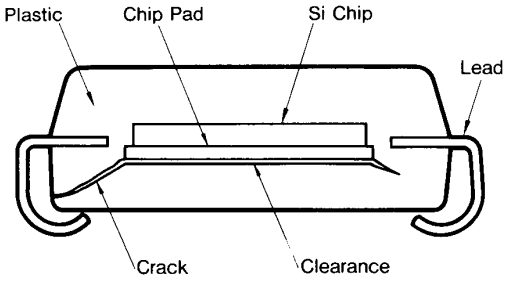

Fig. 2 Package Cracks

where $C_0(x)$ is initial distribution of moisture content and is a function of x only: p, vapor pressure in the space: S, solution coefficient of moisture into the plastic: h, thickness of the plastic below the chip pad and ρ and ρ_s are relative humidity and the saturated vapor pressure of the atmosphere, respectively. In this analysis, saturated moisture content in the plastic is assumed to be proportionate to vapor pressure, i.e., expressed by Henry's law, as shown in Eq. (3) and (4).

The flux J at x=0 which means mass of water supplied into the space per unit area and time is described by the following equation from Fick's first law:

$$J=D\left(\frac{\partial C}{\partial x}\right)_{x=0} . \quad (5)$$

Mass of water in the space is a function of time t and given by integrating Eq. (5) from time $\tau=0$ to $\tau=t$ as follows:

$$m=m_0+A\int_0^t D\left(\frac{\partial C}{\partial x}\right)_{x=0} d\tau , \quad (6)$$

where m_0 is the initial mass of water in the space and A is area of the chip pad.

Assuming elastic deformation of the plastic, volume of the space V is given by:

$$V=\eta\delta A , \quad (7)$$

where η is constant and δ is the maximum clearance of the space. The specific volume of vapor v is given by:

$$v=V/m . \quad (8)$$

The specific volume v is a function of vapor pressure p and temperature T and is described by steam-state equations. In this analysis, Tanishita's equation [4] is employed as follows:

$$v=\frac{461.2T}{p}-\frac{0.668}{(T/100)^{2.7}}-\frac{437+6.44\times10^{-6}p-2.00\times10^{-34}p^5}{(T/100)^{8.4}}-\frac{1.77\times10^{-5}p^5}{(T/100)^{30.5}}-\frac{5.40\times10^{-68}p^{25}}{(T/100)^{147}}, \quad (9)$$

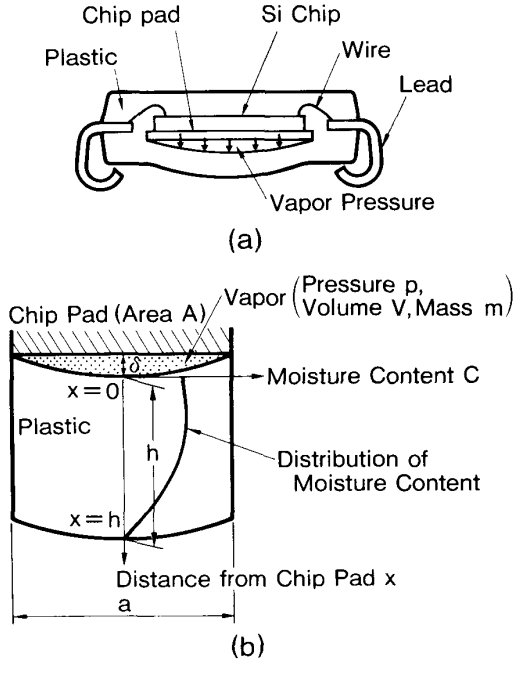

Fig. 3 Analytical Model

where the units of v, p and T are v [m^3/kg], p [Pa] and T [K].

Since the stiffness of the plastic below the chip pad is small enough compared to that of the chip, the chip pad and the plastic above the chip, the plastic below the chip pad can be considered a thin plate and the deformation and stress may be approximated by plate theory [5]. The boundary condition of the plate, however, is not simple. In this analysis, the deformation and stress of the plastic were obtained by the three-dimensional finite element method (FEM).

Small outline J-bend packages (SOJs) are employed for the analysis. Since the shape of these packages is symmetric with respect to the two center lines perpendicularly intersecting each other, one-fourth of the packages are analyzed. The number of nodes and elements of the FEM models are 2535 and 1638, respectively. Pressure acting on the plastic is 0.98 MPa (10 atm).

An example of deformation is shown in Fig. 4. Dotted lines show initial shape and solid lines show shape after loading. Deformation value is magnified to 10 times the size of the model for the figure.

Cases were analyzed with varying size of chip pad, thickness of the plastic below the chip pad and modulus of elasticity of the plastic. It is found that the maximum clearance of the space between chip pad and plastic is given by the following equation for the package with long rectangular chip pad of which aspect ratio is more than 2.5:

$$\delta=0.249\frac{a^{2.91}}{E^{0.93}h^{1.97}}p+\delta_0 , \quad (10)$$

where a is size of chip pad in the short direction: E, modulus of elasticity of the plastic; h, thickness of the plastic and δ_0, the initial clearance. The units of δ, δ_0, a, h are mm and these of p and E are MPa.

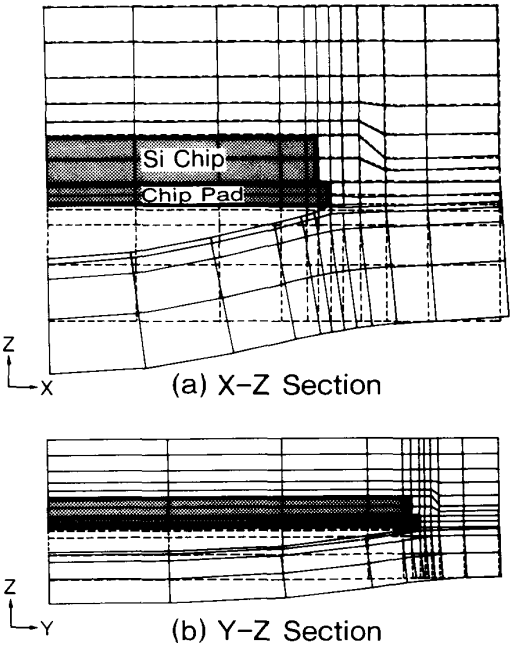

Fig. 4 Deformation of Package by Vapor Pressure

The maximum stress of the plastic generated at the element (element size 0.05×0.1×2.25) adjacent to the center of the long sides of the chip pad is given by:

$$\sigma = 3.15 \frac{a^{1.39}}{h^{1.03}} p \quad . \tag{11}$$

Since the edge tips are singular points within the elastic stress field, the effect of stress concentration on fracture of the plastic must be considered. Fracture of the plastic encapsulant at low temperature can be evaluated by linear fracture mechanics [6]. Investigation of the strength of the plastic at high temperature, however, is not sufficient. For this reason, vapor pressure is employed to evaluate the strength of the plastic and predict whether package will crack during reflow soldering.

If temperature is given as a function of time t, unknown quantities C(x,t), p(t), δ(t) and σ(t) can be obtained by the equations described above. Since the relationships between temperature and time and between properties of the plastic and temperature are nonlinear in general, they cannot be solved analytically. In this study, they were calculated by the finite differential method.

Properties of Plastic at High Temperature

Epoxy resins filled with fused silica are used as plastic encapsulant to limit the thermal expansion coefficient, to improve strength, and to increase moldability [3]. The properties of these plastics change accordingly with content and shape of silica and with the variety of epoxy resin. Although diffusion and solution coefficients, modulus of elasticity and fracture stress are necessary in this analysis, these properties at high temperature have not been obtained. Therefore, the relationships between temperature and these properties were measured in this study.

Diffusion Coefficient

Diffusion coefficient of moisture in the plastic was measured by using plastic specimens whose dimensions are 1×4×13 mm. The specimens were exposed to saturated vapor at 120°C (0.20MPa) for 72 hours to absorb moisture until saturated. Mass of specimens was measured by a chemical balance. Subsequently, they were baked at 60°C, 120°C and 180°C, and the relationship between decrease of mass and time was measured at each temperature. A three-dimensional moisture diffusion analysis of the specimens was performed to determine the diffusion coefficient D. The relationship between the diffusion coefficient and temperature is shown in Fig. 5. The relationship is described by the following Arrhenius equation:

$$D = D_0 \exp\left(-\frac{E_D}{RT}\right) , \tag{12}$$

where T is absolute temperature: E_D, the activation energy; R, the gas constant; E_D=4.84 10^4J/mol, D_0=47.2 mm^2/s.

Solution Coefficient

Solution coefficient of moisture into the plastic was measured by the absorption test of packages at 40°C and 85 percent relative humidity (40°C/95%), 65°C/95%, 85°C/95% and 120°C /100%. The results are shown in Fig. 6. It shows that the relationship between the solution coefficient and temperature can also be described by the Arrhenius equation:

$$S = S_0 \exp\left(-\frac{E_S}{RT}\right) , \tag{13}$$

where E_S=-3.87×10^4J/mol and S_0=4.96×10^{-7}mg/mm^3MPa.

Bending Strength and Modulus of Elasticity

Bending strength and modulus of elasticity of the plastic at high temperature were measured by a three point bending test of specimens with a thickness of 4 mm and width of 13 mm. The results are shown in Fig. 7. Both decrease considerably as the temperature rises and become one-tenth of room temperature values above 200°C. The relationships between the results and temperature expressed by polynominal approximation were used in the analysis.

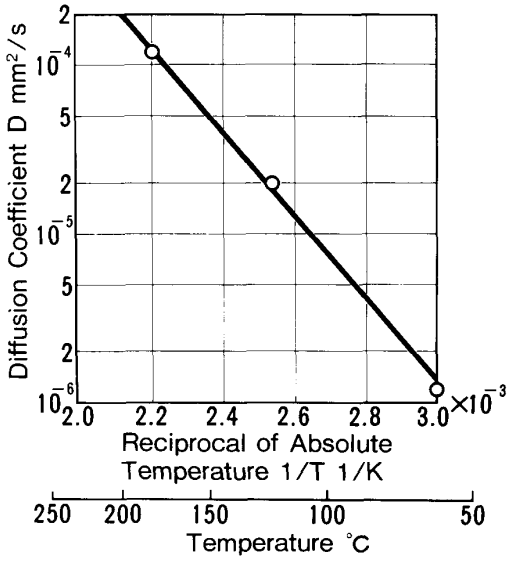

Fig. 5 Diffusion Coefficient of Moisture in the Plastic

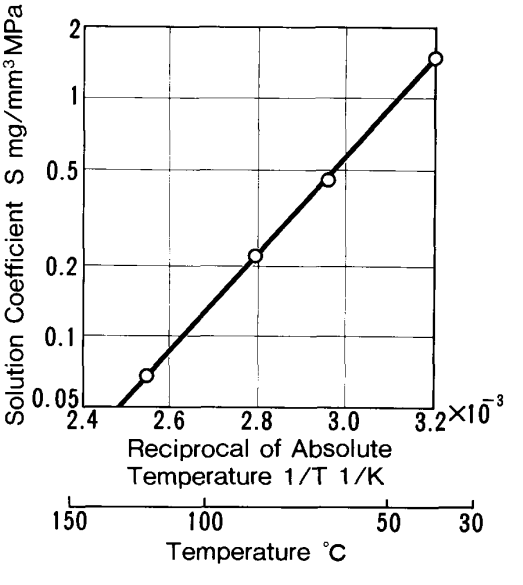

Fig. 6 Solution Coefficient of Moisture into the Plastic

Deformation of Package during IR Soldering

In order to check the propriety of the present analysis, deformations of the packages when cracking occurred during IR heating were measured and compared with the calculated value by the present analysis.

Experimental Method

The experimental equipment is shown in Fig. 8(a). An SOJ package was placed on a hard heat insulator and a fused silica needle with a 0.8 mm diameter was set upright on the center of the package. A metal chip was attached to the top of the needle to measure the displacement by a non-contact detector. The measured displacement was considered to be deformation value of the package. The package was heated by a 100 W IR heater. The temperature profile was measured by a thermocouple with a 0.1 mm diameter placed in the interface between the chip pad and the plastic as shown in Fig. 8(b).

The packages were tested after being exposed to saturated vapor at 120°C to absorb moisture until saturated. Displacement observed in this experiment includes thermal expansion of the package, bending deformation due to temperature distribution and mismatch of thermal expansion coefficients of the components and thermal drift of the detector. Therefore dried packages were also tested under the same conditions and the differences between the displacement of moisture absorbed packages and that of dried packages were considered to be the clearance between chip pad and plastic caused by vapor pressure.

Experimental Result

Measured temperature profile is shown in Fig. 9. The rate of rising temperature above 150°C was about 3°C/s, which is one-tenth the rate used in the general reflow soldering process.

Change in clearance is shown in Fig. 10. Package cracking occurred at 33 or 34 seconds after beginning heating. Deformation changed suddenly just before the cracking.

Experimental results were simulated by the present analysis. Temperature profile shown in Fig. 9 was approximated with following equation:

$$T=22+0.916t+23.63\sqrt{t}\ , \qquad (14)$$

where T is in C and t, seconds. Solid line in Fig. 10 shows calculated results, which approximately agree with the experimental results. The validity of the present analysis is considered to be confirmed.

Change of vapor pressure during the experiment is

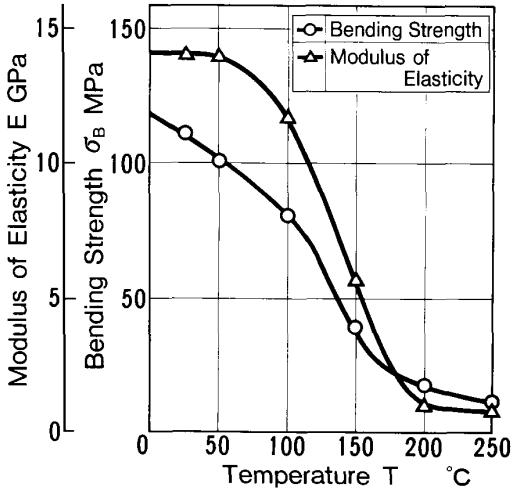

Fig. 7 Bending Strength and Modulus of Elasticity of the Plastic

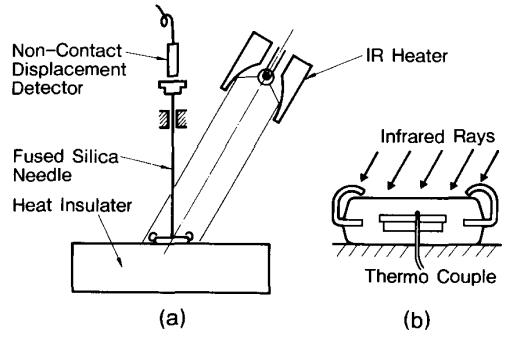

Fig. 8 Experimental Equipment

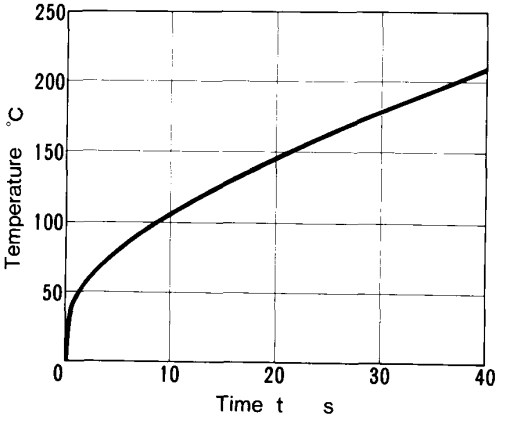

Fig. 9 Temperature Profile

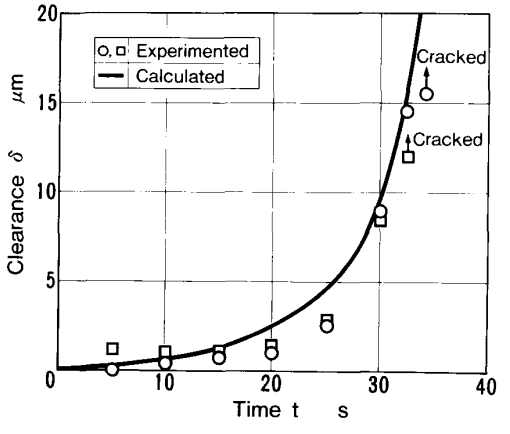

Fig. 10 Change of Clearance

shown in Fig. 11. The saturated vapor pressure at each temperature is also shown for reference. Although generated vapor pressure equals saturated vapor pressure at the beginning of heating, generated pressure values are lower than those for saturated pressure with increasing of temperature. This is due to insufficient rate of moisture diffusion into the space and to the equilibrium state of the vapor and moisture. Since saturated moisture content of plastic increases with increasing temperature, generated vapor in the space could exist in equilibrium with the moisture at lower pressure than saturated vapor pressure.

Relationship between Package Cracking and Condition of Moisture Absorption

The level of moisture saturation (determing ratio of the actual absorbed moisture mass to the saturated absorbed moisture mass) has been generally used to evaluate package cracking. To check the validity of this evaluation method, several packages with different level of moisture saturation were heated up to 215 °C by VP soldering equipment and existence of package cracks was investigated. To produce different level of moisture saturation, a two-way experiment was performed. One group of packages was dried completely and was exposed to 85°C/85%. The other group was exposed to 85°C/85% until saturated and was baked at 80 °C in dry air. The relationship between the level of moisture saturation and the absorption or desorption time is shown in Fig. 12. The blackened symbols represent the packages which were cracked during VP soldering and open ones represent those not cracked. Although the cracking limit level of moisture saturation for absorption is about 75%, that at desorption is about 25%. As is obvious from this experiment, the package cracking depends on not only the level of moisture saturation of the package but also the hysteresis of moisture absorption. Therefore, evaluation by the level of moisture saturation method is not always appropriate. It is considered that the difference due to the hysteresis is caused by the distribution of moisture content in the package. Moisture content at the part of the plastic facing the space has the greatest influence on the generation of vapor, and it does not correspond to the average level of moisture saturation. It is considered that the moisture content at that part is always lower than the average moisture content at absorption and is always higher at desorption.

In order to confirm this hypothesis, the change of distribution of moisture content in the plastic at absorption and desorption was calculated by the present analysis. The results are shown in Fig. 13. The moisture contents at the interface when package cracking occurred at absorption (34 hours) and at desorption (26 hours) are 63% and 60% respectively, and are in approximate agreement. It is found that package cracking depends on the moisture content of the plastic at the interface.

Vapor pressure generated inside the space between the chip pad and the plastic is analyzed by the present method and the results are shown in Fig. 14. Vapor pressure values corresponding to the cracking limit time at absorption and desorption almost coincide.

As seen from this example, it is possible to evaluate the strength of the package against cracking by the present analysis method quantitatively.

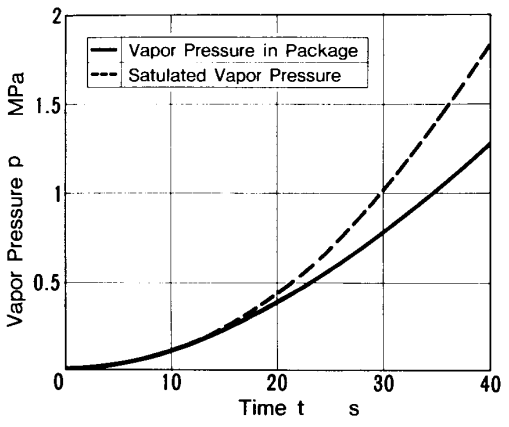

Fig. 11 Change of Vapor Pressure

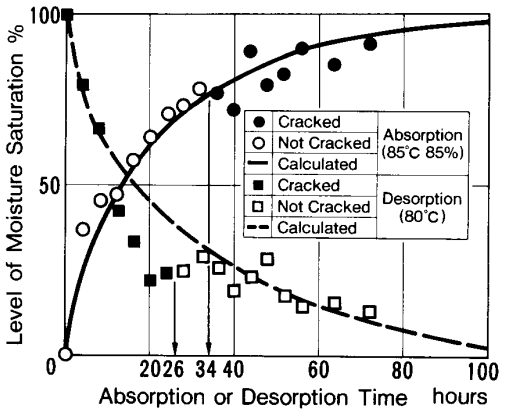

Fig. 12 Relationship between Level of Moisture Saturation and Time

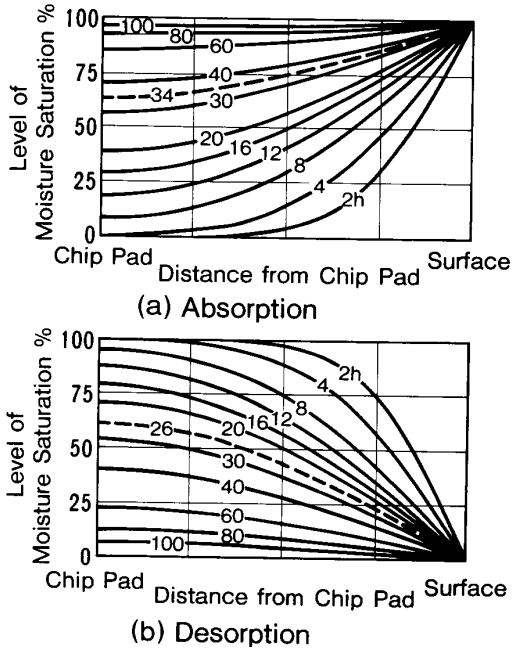

Fig. 13 Moisture Content Distribution

Package Cracking Conditions

The factors which influence package cracking are considered to be as follows:
(1) Level of moisture saturation and hysteresis of moisture absorption.
(2) Structure of package.
(3) Strength of plastic encapsulant.

Package cracking occurrence is shown schematically in Fig. 15. x-axis shows the increasing temperature of a package during reflow soldering and y-axis shows the strength and the maximum stress of the plastic at each temperature. Maximum stress of the plastic changes like A, B or C in Fig. 15, for example. Maximum stress is determined by the structure of the package, the level of moisture saturation and the hysteresis of moisture absorption. Since the strength of the plastic decreases with increasing temperature, package cracking occurs at the temperature when maximum stress exceeds strength. Assuming reflow temperature to be 215°C, package cracking occurs in the cases of A and B and does not occur in the case of C.

Methods of preventing package cracking corresponding to the above factors are considered to be as follows:
(1) Prevent the package from absorbing moisture.
(2) Design structure of package to decrease maximum stress of plastic due to vapor pressure.
(3) Develop plastic with high strength at high temperature.

The first method is studied by wrapping packages with moisture protective film [7]. Wrapped packages can be stored 10 times as long as unwrapped ones. Another methods are also being studied by the present analysis.

Conclusions

To evaluate package cracking which occurs in SMDs that have absorbed moisture, a moisture diffusion analysis in the plastic, a deformation and stress analysis of the package and measurement of some properties of plastic at high temperature are performed. The validity of the analysis is confirmed by a measurement of deformation of packages which are heated by IR.

Several packages with different level of moisture saturation and hysteresis of moisture absorption are heated by VP soldering and existence of package crack is investigated. Vapor pressure and distribution of moisture content of these packages are calculated by the present analysis. It is found that generated vapor pressure is lower than saturated vapor pressure and depends on the moisture content at the part of the plastic facing the space where vapor pressure is generated. As seen from this example, it is possible to evaluate package cracking by the present analysis method quantitatively.

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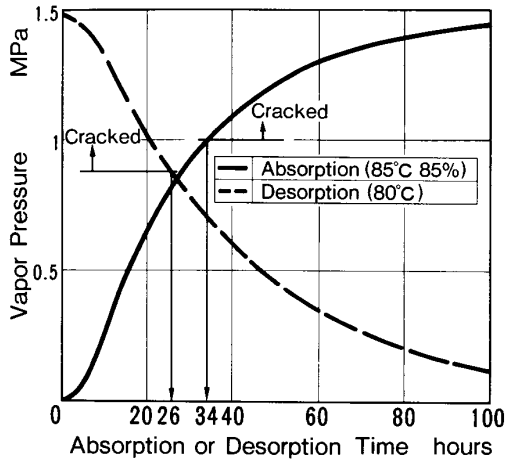

Fig. 14 Vapor Pressure in the Package during VP Soldering

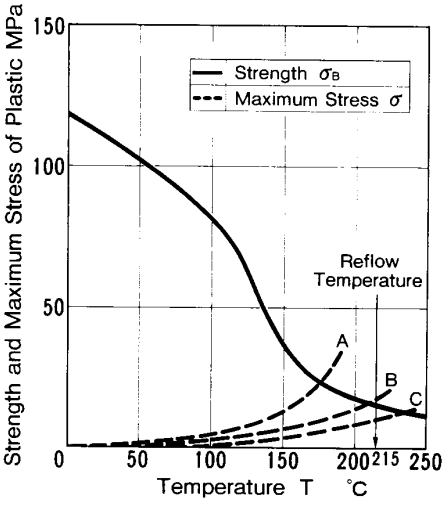

Fig. 15 Package Cracking Conditions