Dynamic Growth of Voids under Effects of Thermal and Vapor Pressure in Electronic Packaging

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Abstract The failure can be caused in polymers by thermal stress and vapor pressure during reflow process. A profound view on dynamic growth of voids during reflow process is provided in this paper. The mechanical model is analyzed at first. Then the dynamic equation is derived via the energy method. Furthermore, we apply the method to numerically solve the dynamic increase of void volume fraction under the linear-elastic model. Also, the increase proceeding under different Young's Modulus is compared. It is interesting that the final void volume fraction remain constant when the Young's Modulus keeps unchanged during the reflow process. At last, the dynamic growth curves on the assumption of super-elastic constitution under different initial void volume fraction are compared. It is notable that the initial void volume fraction is extraordinarily significant for the eventual deformation.

Keywords Polymers, dynamic growth, vapor pressure, electronic packaging

1. Introduction

Polymer materials have wide applications in industry such as being adhesive film in the microelectronic packaging. However, polymers are of high porosity which influences the reliability of electronic packing. Besides, most of polymers are hydrophilic materials which are capable of absorbing a large number of moisture in ambient environment. According to the requirement of electronic packaging, electronic devices would experience a reflow process which is completed within a few minutes. The peak temperature of devices during this process typically ranges from 220℃ and 260℃, consequently moisture stored in polymer materials vaporizes and becomes vapor pressure which also pose serious threat on the reliability of package[1-3]. With regard to instable growth of micro-voids, there are a large number of works related to the field. Ball[4] investigated discontinuous equilibrium solutions of cavitations in the year of 1982. Based upon Ball's theory, Lopez-Pamies et al. [5-6] put forward the defect-growth theory. As to the failure of cavitations caused by vapor pressure, Fan et al. [7] derived a micromechanics based vapor pressure model, Huang et al. [8-9] studied cavitations' instabilities of a central hole in an infinite plate subjected to distributing pressure. And then, Guo et al. [10-12] investigated instabilities of micro-voids subjected pressure on the inner boundary and thermal stress on the outer boundary. Also, there are some literature investigating the cavitation instability in different packaging materials[13-15].However, the former work mainly focuses on the critical load of instable growth of micro-voids. Actually, it is also significant to produce a profound understanding of the dynamic growth process of voids, which will be beneficial to the industrial design. In the industry of electronic packaging, we can control the temperature to optimal processing when electronic devices are manufactured. Therefore, it is of great importance to acquire the responding increase of micro-voids with respect to time.

The outline of the paper is organized as follows: In Section 2, the mechanical model is built up. In Section 3 the energy principle is introduced to derive the transient growth equation of micro-voids to help further the discussion in the next section. In Section3, we utilize the equations in Section 3 to obtain the curve of growth of micro-voids as the time increases under the elastic and super-elastic models, respectively. In the end, the results obtained are compared, and some intriguing phenomena appear through our analysis. This paper will present a good understanding on how the void growth during reflow process, and will benefit the engineer’s design of polymer materials in this industry.

2 Formulation of Mechanical Model

The moisture absorbed by the electronic materials is trapped in numerous pores (or micro-voids). During reflow process, the temperature of the package is raised to about 220℃ or more, which induce the evaporation of moisture in micro-voids. Thus, the micro-voids are subjected to internal vapor pressure p and remote stress σ_r^A, which denotes the thermal stress due to the increased temperature . For the purpose of analysis, it is convenient to consider a spherical volume of material containing a micro-void of spherical shape with initial inner radius R_1 and outer radius R_2. We assume that the matrix material is incompressible. And the micro-void will enlarge when it subjected to the combined effort of vapor pressure p and thermal stress σ_r^A. Therefore, we assume the r_1 and r_2 as the inner and outer radius after deformation. The mechanical model is displayed in Fig. 1.

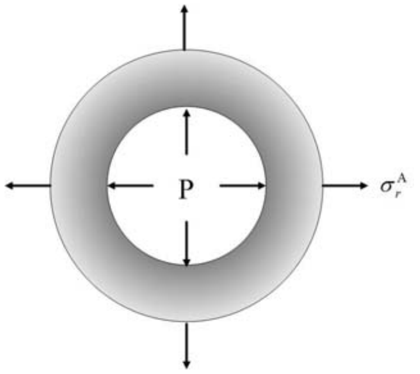

Fig. 1 The mechanical model of micro-voids under the action of vapor pressure and thermal stress

The micro-void is geometrically characterized by the initial and current void volume fractions f_0 and f:

$$f_0 = (\frac{R_1}{R_2})^3 \qquad , \qquad f = (\frac{r_1}{r_2})^3$$

There are numerous vapor pressure models based on various theories. vapor pressure p satisfies the ideal gas law, then the vapor pressure model we use is shown as follows[16]:

$$P = P_0 \frac{T}{T_0} \frac{f_0}{f} \frac{1-f}{1-f_0} \mathrm{e}^{-3\alpha\Delta T} \tag{1}$$

Where p_0 is the initial pressure at room temperature, T represents current temperature, T_0 denotes initial temperature, α represents coefficient of heat expansion, $\Delta T = T - T_0$. During the reflow process in electronic packaging , temperature loading mode will reach the peak temperature more than 220℃, and temperature variation could be represented as the function of time t. Fig.2 displays a kind of temperature loading process with respect to the time.

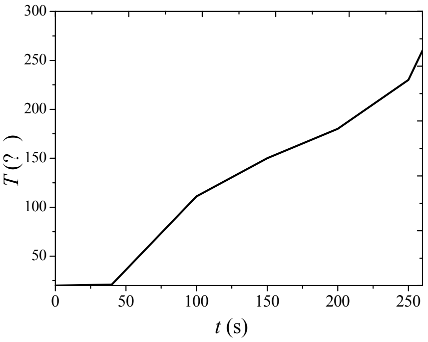

Fig.2 A typical temperature loading

How to utilize the variational principle to derive the growth function of micro-void? Firstly, we describe an arbitrary point(R, Θ, Φ) in the spherical coordinates in the initial configuration, and (r, θ, φ) represents the corresponding coordinates in the deformed micro-voids. It is notable that the deformation is spherically symmetric, therefore

$$\mathrm{r}=r(R),\theta=\Theta,\ \varphi=\Phi \tag{2}$$

Therefore, the domain before deformation is

$$D_0=\{(R,\Theta,\Phi)\,|\,0\le R_1\le R_0<R_2,0<\Theta\le 2\pi,0\le\Phi\le\pi\}$$

According to spherically symmetry, domain after deformation is

$$D=\{(r,\theta,\varphi)\,|\,r=(R)\ge 0,\ \ R_1\le R\le R_2,\Theta=\theta,\Phi=\varphi\}$$

Because of the condition of incompressibility, the volume relation below can be obtained:

$$r^3-r_1^3=R^3-R_1^3 \tag{3}$$

In terms of Eq. (2), the current void volume fraction can be displayed as

$$f=\frac{f_0a^3}{1-f_0+f_0a^3} \tag{4}$$

Where $a=r_1/R_1$ denotes the growth ratio of the micro-void.

3 Derivation of Governing Equation

In the section above, the geometrical configuration has been described. In this section, the fundamental formulation will be discussed in detail. We denote W as the strain energy function of the electronic packages. As to the linearly elastic material, the function is well-known for us[17]. When the ambient temperature is relatively higher or the materials themselves are soft, the super-elastic model should be taken into account. There are a vast amount of super-elastic models. In this paper, the neo-Hookean strain energy function will be introduced when the super-elastic analysis is conducted. The function of neo-Hookean material can be written as

$$W=\frac{\mu}{2}(\lambda_r^2+\lambda_\theta^2+\lambda_\phi^2-3) \tag{5}$$

Where, λ_r, λ_θ, λ_ϕ represent the principal stretches in the respective directions, respectively. Cauchy stress components in spherical coordinate system (r, θ, φ) corresponding to neo-Hookean materials are shown below:

$$\sigma_r=\lambda_r\frac{\partial W}{\partial\lambda_r}, \qquad \sigma_\theta=\sigma_\phi=\lambda_\theta\frac{\partial W}{\partial\lambda_\theta} \tag{6}$$

Also, the principal stretches in the respective directions can also be described as:

$$\lambda_r=\frac{dr}{dR}=r'(R), \qquad \lambda_\theta=\lambda_\phi=\frac{r(R)}{R} \tag{7}$$

The total potential energy can be expressed as follows:

$$E=\int_{R_1}^{R_2}4\pi R^2W(\lambda_r,\lambda_\theta,\lambda_\phi)dR-\int_{R_1}^{r_1}4\pi R^2p\left(R\right)dR+\int_{R_2}^{r_2}4\pi R^2\sigma_r^A dR \tag{8}$$

According to the principle of least potential energy, we can obtain the governing equation from the first term in total potential energy after variation. Taking the Eq. (4)-(6) into the newly obtained variatianal equation, the governing function of dynamic growth of micro-void can be formulated.

4 Results and Discuss

In the last section, the derivation of governing function is discussed. In this section, we apply the method discussd above to predict that how void volume fraction f increase with respect to the time.

If we assume the material is linearly elastic, the governing function is shown as follows:

$$\frac{df}{dt}=\frac{9p_0f_0(f_0-f)f(1-f)(1-3\alpha T)\dfrac{dT}{dt}}{4ET_0(1-f_0)f^2e^{3\alpha\Delta T}[\dfrac{f_0}{f}\ln\dfrac{f_0}{f}\dfrac{1-f}{1-f_0}-\ln\dfrac{1-f}{1-f_0}]+9p_0f_0(f_0-f)T} \tag{9}$$

Where E is the Young's modulus of polymer materials applied in electronic devices. Due to the limited influence of thermal loading,thermal stress can be ignored, which means that the vapor pressure plays the major part on the growth of micro-voids on the proceeding of reflow. It is obvious that Eq. (9) is a IVP which can be solved numerically. The initial condition is that when t=0, f=f_0.Another problem is that as the loading temperature increases, the polymer materials will undoubtedly become softer and softer. As a result, the Young's modulus will decrease sharply. Hence, we compare three types of Young's modulus: 1GPa, 0.1GPa and linear decrease from 1GPa to 0.1GPa. The other parameters are selected as follows : f_0=1%, P_0=0.1MPa, T=0.94t+T_0, T_0=25℃， $\alpha=1.5\times10^{-4}$.The growth of f as the time goes on is demonstrated in Fig. 3.

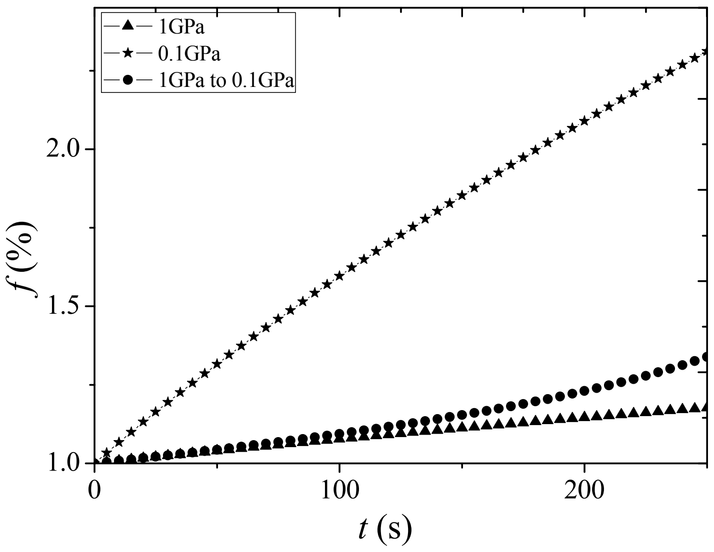

Fig.3 Dynamic growth of micro-void under different Young's Modulus

As it shown in Fig. 3, it is clearly to see the growth of cavitation during reflow process .and it is also notable that the soften the material are , the larger the deformation of micro-void is . In the electronic industry, it is not difficult for us to measure the Young's modulus of polymer materials with regards to different temperature. Thereby, we can accurately simulate the dynamic growth of micro-void regarding to variation of Young's modulus. In addition, the method of temperature loading also influences the transient growth of micro-voids. If the temperature T is non-linearly dependent with time t, the whole increase of void volume fraction will be different from the result in Fig. 3. Fig. 4 depicts the compassion between the linear temperature loading and quadratic temperature loading (T=0.003t^2+0.19t+T_0). We can see that when the temperature loading change, the void will increase in another way. However, it is intriguing to find that the final void volume fraction after the reflow process is the same no matter how matter the temperature is loaded in linear form or quadratic form if the Young's modulus remains unchanged with increasing temperature. However, if Young's modulus of materials varies with temperature, the fascinate phenomenon will not appear.

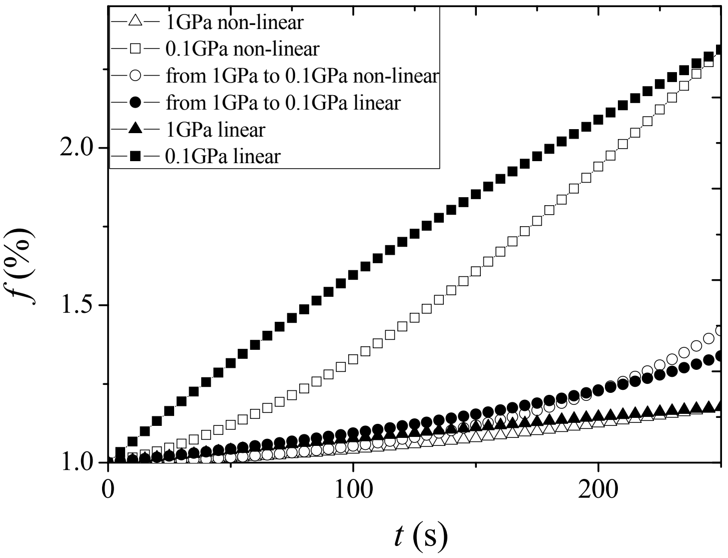

Fig. 4 Comparison between dynamic growth of micro-void under different temperature loadings

In reality, it is impossible for most of polymer materials to maintain the property of linear elasticity. In most of cases, polymers behave as super-elasticity even at the room temperature. The neo-Hookean model is one of the most common models applied in polymer materials. The dynamic growth equation can also be derived via the same method discussed above:

$$\frac{df}{dt}=\frac{P_0 f_0 f(1-f)(1-3\alpha T)\,dT/dt}{2\mu T_0(1-f_0)f^2 e^{3\alpha\Delta T}\{\frac{f_0}{f^2}[(\frac{f_0}{f}\frac{1-f}{1-f_0})^{-\frac{2}{3}}+(\frac{f_0}{f}\frac{1-f}{1-f_0})^{\frac{1}{3}}]-(\frac{1-f}{1-f_0})^{\frac{1}{3}}-(\frac{1-f}{1-f_0})^{-\frac{2}{3}}\}+P_0 f_0 T} \tag{10}$$

The shear modulus μ is set to 333 MPa ,and other variables is of the same value with that in the former discussion. The void growth is shown in Fig. 5. It is notable that the increase of void volume fraction is closely dependent on the value of initial void volume fraction.

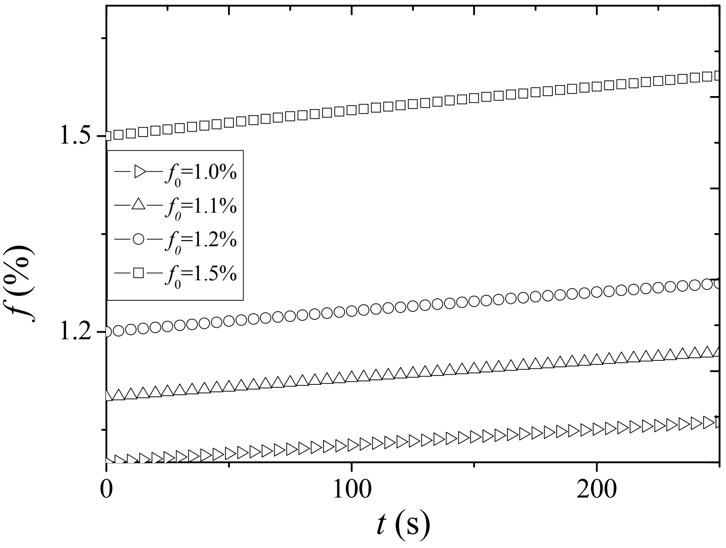

Fig.5 Dynamic growth of super- elastic micro-void under various initial void volume fraction

5 Conclusions

In this paper, theoretical results for dynamic growth of micro-voids are obtained with the context of finite deformation. The numerical method is applied to calculate the deformation of a void under the constitutional model of linear elasticity and super-elasticity. According to results acquired, it is notable that ways of growth are completely different when the temperature loadings are various. Secondly, when the Young's Modulus remains constant, the consequent that the final value of f will never change is fascinating. At last, the increase of void volume fraction is extremely dependent on the initial void volume fraction. Our investigation will provide a good understanding of mechanism of dynamic growth for engineers and researchers.

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