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Application of a Genetic Algorithm Associated With Adhesive Joint Analysis to the IC Chip Pick-up Process

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Abstract
In the condition investigated here, a concentrated force is applied to both IC chip and blue tape bonded by an adhesive under pin–pin boundary conditions. The experimental results show that even though IC chips of 0.1 mm thickness are subjected to a concentrated force of 4.8 N, they cannot be fully separated from the blue tape and fail easily during the pick-up process. However, when IC chips of 0.34 mm thickness are subjected to a concentrated force of only 3.5 N, they can be fully separated from the blue tape without breakage. These two experimental findings are then explored analytically by applying the C++ program of the genetic algorithm associated with adhesively bonded joint analysis to the IC chip pick-up process. In accordance with the experimental results, the results for the 0.1 mm thick IC chips reveal no solutions for the material properties or adhesive thickness to satisfy the conditions of the IC chip successful pick-up process, although those for the 0.34 mm thick IC chips show solutions for the values of both the elastic modulus and the adhesive layer's thickness. As regards the easy failure of IC chips with 0.1 mm thickness, if the blue tape's mechanical properties are appropriately chosen and then used in this process and its elastic modulus is greater than one-tenth that of the IC chips, the probability of the IC chips being fully separated from the blue tape can be expected to increase.

Keywords
Joint, adhesive, genetic algorithm, IC pick-up process, concentrated force

1. Introduction

Recently, the everyday use of portable 3C (computer, communication, consumer) products has become widespread as lighter, thinner, shorter, smaller, multifunctional products have grown in popularity and ease of use. As a result, IC (integrated

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circuit) chips also have to become thinner and smaller to fit the size of lighter and smaller products. However, as IC chips become thinner, they fail more easily during the IC chip pick-up process (an IC manufacturing step in the dicing process of the back-end processing procedure). That is, the thinner the IC chips become, the lower is their success rate in the IC chip pick-up process.

For the diamond cutter to slice the wafer into pieces (i.e., into IC chips) during the dicing process, the wafer must be bonded to the blue tape (forming the so-called adhesively bonded joint of IC chip, adhesive, and blue tape named because tape's color is blue) using an adhesive strong enough to prevent the cutting force from separating the wafer from the tape. In other words, the strength of the adhesive must satisfy the bond strength required in the dicing process. However, once cutting is accomplished, in order to make the IC package, the adhesively bonded IC chips must be separated from the tape so that a force applied to the blue tape through a lower-speed piercer [24] is high enough to break the adhesively bonded joint between the IC chips and the blue tape without breaking the IC chips. To this end, the adhesive's bond strength is reduced by exposing the bonded joint to ultraviolet (UV) light after cutting. This reduced bond strength in the IC chip pick-up process enables complete separation of the IC chips from the blue tape without breakage.

In this study, analyzing the adhesively bonded joint in the IC chip pick-up process is similar to analyzing a single-lap joint investigated by many researchers [1–3]. Also Suhir [4] studied the effect of thermal variation on adhesive joint stress distributions.

Tsai and Morton [5] analyzed the single-lap joint using a two-dimensional, geometrically nonlinear, finite element analysis. Subsequently, Luo and Tong [6] applied linear and higher order displacement theories to the stress analysis of thick adhesive layer.

Some studies have investigated the plastic behavior in adhesive joints using FEM and analytical methods [7–10]. Generally, a single-lap joint is analyzed using one of two methods: the analytical method, which allows derivation of closed-form solutions and clarifies the relationships among the geometrical parameters and physical phenomena, or the finite element method. The latter method, however, is unsuitable for the present study where IC chips' length is much greater than their thickness and adhesive thickness is considered as a design variable in the optimum search, because these conditions make it more difficult for FEM to produce accurate numerical solutions. That is, generating a finer mesh of adhesive, IC chip and blue tape is problematic if either the ratio of the adhesive thickness to the joint length or the ratio of the IC chip thickness to its length is very small. Especially for this study, as the adhesive thickness evidently affecting stress distribution in the adhesive joint is considered as a design variable in the optimum search, mesh density of adhesive is necessarily varied with the adhesive thickness and mesh density also has to be locally increased at the both ends of the joint. Moreover, as adhesive thickness is varied with each search step of genetic algorithm, the mesh problem for the adhesive joint has more difficulty in achieving an accurate numerical solution. In other words, not only achieving an accurate numerical solution requires far more CPU run time, the joint must also have a much finer mesh. Thus, the analytical solutions [23] for the adhesively bonded joint were developed instead of finite element method because of less CPU run time required to analyze the joint. As these solutions were used to analyze an adhesively bonded joint, this analysis took only less than 3 s (a Duo-Core T2300 PC computer with a 512 Mbyte RAM and a 1.6 GMz CPU).

After reviewing related literature, genetic algorithms (GAs) and the penalty function method were employed to investigate the conditions for the IC chip successful pick-up process as the geometrical dimensions and material properties of an adhesively bonded joint have great effects on the stress distributions in the adhesive [23]. The given values of penalty parameters, and penalty function methods are discussed below. To solve real-world search and optimization problems involving inequality and/or equality constraints, some authors have employed genetic algorithms and the penalty function method that requires no penalty parameter [11–14]. Other authors have proposed penalty schemes and adaptive search techniques to improve the efficiency of the GAs [15–18]. Wu and Chow [19] applied genetic algorithms to a constrained nonlinear optimization problem using a mix of discrete sizing and continuous configuration variables; and Kwon *et al.* [20] proposed a successive zooming genetic algorithm (SZGA) for identifying a global minimum using continuous zooming factors. Overall, GAs have been applied to these proposed studies [21, 22].

The key factors affecting the success rate in the IC pick-up process include the properties of the adhesive and the blue tape. Specifically, the thinner the adhesive and the IC chip, the more the success rate in the IC chip pick-up process is affected by the adhesive thickness because stress distributions of the adhesively bonded joint has a larger variation with adhesive thickness [23]. Moreover, the adhesive stresses are obviously affected by certain of the adhesive's geometrical parameters relative to the IC chips and blue tape. Particularly, as the IC chips become thinner — for example, when their thickness is 0.1 mm — they are more likely to fail during the IC chip pick-up process. In contrast, when the IC chip thickness is 0.34 mm, the success rate is nearly 100% for the same adhesive and blue tape. These results were first obtained experimentally [24] using the MIRI CP602 IC chip pick-up machine produced by the Industrial Technology Research Institute (Hsinchu, Taiwan, R.O.C.).

The aim of the current investigation was to improve the success rate of the 0.1 mm thick IC chips in the IC chip pick-up process. Specifically, we explore the different results obtained for IC chip thicknesses of 0.1 and 0.34 mm during this process. Because it is difficult to select the most suitable adhesive among numerous types, the study employs a two-variable optimum search method to gauge the effect of the adhesive's characteristics and elastic moduli of the blue tape on the success rate in the IC chip pick-up process. Rather than the adhesive used by Cheng *et al.*

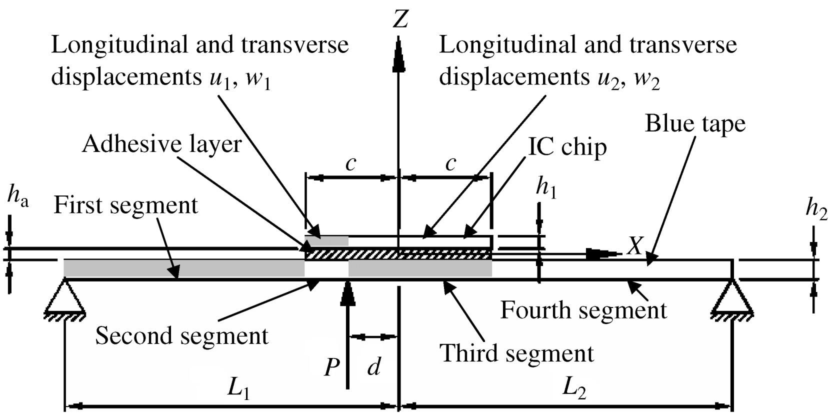

Figure 1. Sketch showing IC chip and blue tape bonded by an adhesive layer.

[24], this study used general types of adhesives in the IC chip pick-up process to eliminate the step of exposing the IC chips to UV light.

2. Mathematical Model

A sketch with the following geometric parameters is shown in Fig. 1. First, an IC chip and the blue tape are bonded together by the adhesive (i.e., the model consists of the IC chip, blue tape, and adhesive layer). The origin of the coordinates is located in the center of the adhesive layer. The thicknesses of the IC chip, blue tape, and adhesive layer are h_1, h_2 and h_a, respectively; their lengths are represented by $2c$, $(L_1 + L_2)$ and $2c$, respectively. The blue tape of the model with a pin–pin boundary condition is subjected to a concentrated force, P (i.e. the maximum force obtained by measuring the maximum value of the force applied to the blue tape through the lower-speed piercer during the IC pick-up process). Because of the piercer being at this lower speed, the model is studied using quasistatic analysis.

As already pointed out, the mesh problem resulting from the high ratios of the thicknesses of the adhesive layer, IC chip and blue tape to the length of their joint makes it difficult to obtain accurate solutions in the finite element method. Rather, complicated and sophisticated analytical solutions are generally derived using symbolic manipulation in a Mathematica package, after which numerical solutions are obtained using singular value decomposition (SVD) for an inverse matrix. Such analytical solutions for the model can be described simply as follows, and a detailed discussion about these solutions can be found in reference [23].

First, the blue tape is divided into four segments whose ranges are $-L_1 \leqslant x \leqslant -c$, $-c \leqslant x \leqslant -d$, $-d \leqslant x \leqslant c$ and $c \leqslant x \leqslant L_2$, on the x-axis. Next, the IC chip is divided into two segments whose ranges are $-c \leqslant x \leqslant -d$ and $-d \leqslant x \leqslant c$ on the x-axis. Finally, the adhesive layer is also divided into two segments, each of which has the same range as the corresponding segment in the IC chip.

For the IC chip, the subscripts i of u_i and w_i represent the $(i-1)$th segment of IC chip. Furthermore, u_i and w_i ($i = 2$ or 3) represent, respectively, longitudinal and transverse displacements where $i = 2$ represents the first segment ($-c \leqslant x \leqslant -d$) and $i = 3$ represents its second segment ($-d \leqslant x \leqslant c$).

2.1. Transverse and Longitudinal Displacements in the IC Chip and Blue Tape

Assuming that the transverse displacements w_i of the IC chip are written in the following form:

$$\begin{aligned} w_i &= c_{i0} + c_{i1}x + c_{i2}x^2 + c_{i3}x^3 + c_{i4}x^4 + c_{i5}x^5 + c_{i6}\overline{\mathrm{Ch}} \\ &\quad + c_{i7}\overline{\mathrm{Sh}} + \overline{\mathrm{Ch}}_1(c_{i8}\bar{\mathrm{C}} + c_{i9}\bar{\mathrm{S}}) + \overline{\mathrm{Sh}}_1(c_{i10}\bar{\mathrm{C}} + c_{i11}\bar{\mathrm{S}}), \quad i = 2 \text{ or } 3, \end{aligned} \tag{1}$$

where $\overline{\mathrm{Ch}} = \cosh(\alpha x)$, $\overline{\mathrm{Sh}} = \sinh(\alpha x)$, $\overline{\mathrm{Ch}}_1 = \cosh(\alpha_{11}x)$, $\overline{\mathrm{Sh}}_1 = \sinh(\alpha_{11}x)$, and the unknown constants are $c_{ij}, i = 2$ or 3, $j = 0$–11, $\bar{\mathrm{C}} = \cos(\alpha_{12}x)$ and $\bar{\mathrm{S}} = \sin(\alpha_{12}x)$; α, and $\pm\alpha_{11} \pm i\alpha_{12}$ are the characteristic solutions (i.e., the characteristic equation $\det|\mathbf{A_D}| = 0$) to the following equations (see equation (38) of Cheng *et al.* [23]):

$$\begin{aligned} &\begin{bmatrix} D^2 - \frac{1}{E_1\beta_1h_a^2} & \frac{1}{E_1\beta_1h_a^2} & -\frac{\beta_1h_a}{2}D^3 - \frac{1}{E_1\beta_1h_a}D & 0 \\ \frac{1}{E_2\beta_2h_a^2} & D^2 - \frac{1}{E_2\beta_2h_a^2} & 0 & \frac{\beta_2h_a}{2}D^3 + \frac{1}{E_2\beta_2h_a}D \\ \frac{6}{\beta_1h_a}D^3 & 0 & -4D^4 - \frac{1}{h_ad_1} & \frac{1}{h_ad_1} \\ 0 & -\frac{6}{\beta_2h_a}D^3 & \frac{1}{h_ad_2} & -4D^4 - \frac{1}{h_ad_2} \end{bmatrix} \begin{bmatrix} \tilde{u}_i \\ \tilde{u}_{ix} \\ w_i \\ w_{ix} \end{bmatrix} \\ &= [\mathbf{A_D}][u] = 0, \end{aligned} \tag{2}$$

where $\tilde{u}_i = u_i(h_a/2)$, $\tilde{u}_{ix} = u_{ix}(-h_a/2)$ and $D = d/dx$, i may be either 2 or 3. The nondimensional terms are $\beta_1 = h_1/h_a$, $\beta_2 = h_2/h_a$, $E_1 = E_1^*/G_a$, $E_0 = E_a/G_a$ and $E_2 = E_2^*/G_a$, and the other parameters are $d_1 = h_1^3E_1^*/(12E_a)$, $d_2 = h_2^3E_2^*/(12E_a)$. The symbols E_2^* and E_1^* represent the elastic moduli of the IC chip and of the blue tape; the shear modulus, the elastic modulus, and the thickness of the adhesive layer are denoted by G_a, E_a and h_a, respectively.

Substituting equation (1) into equation (2), analytical solutions for the longitudinal displacements $\tilde{u}_i$ ($i = 2$ or 3) can be derived through symbolic manipulation in terms of c_{ij}, $\bar{\mathrm{S}}$, $\bar{\mathrm{C}}$, $\overline{\mathrm{Ch}}$, $\overline{\mathrm{Sh}}$, $\overline{\mathrm{Ch}}_1$ and $\overline{\mathrm{Sh}}_1$.

For the blue tape, the subscripts ix of u_{ix} and w_{ix} represent the ith segment of blue tape. Furthermore, when $i = 1$, transverse and longitudinal displacements of the first segment are denoted, respectively, by w_{1x}, u_{1x}. Likewise, when $i = 2, 3$, or 4, those for the second, third, or fourth segments are denoted by w_{2x}, u_{2x}, w_{3x}, u_{3x}, or w_{4x}, u_{4x}, respectively.

The transverse and longitudinal displacements of the first and fourth segments are given below:

$$w_{1x} = -\frac{2\tilde{F}_L(3L_1x^2 + x^3)}{E_2h_2^3} + c_{11}x + c_{12}, \quad -L_1 \leqslant x \leqslant -c, \tag{3}$$

$$u_{1x} = \frac{1}{E_2}\left(\frac{\tilde{N}_{\mathrm{L}}}{h_2}x - \frac{6\tilde{F}_L(2L_1x + x^2)z''}{h_2^3}\right) + c_{13}, \quad -L_1 \leqslant x \leqslant -c, \tag{4}$$

$$w_{4x} = -\frac{2(\tilde{P} - \tilde{F}_{\mathrm{L}})(3L_2x^2 - x^3)}{E_2h_2^3} + c_{41}x + c_{42}, \quad c \leqslant x \leqslant L_2, \tag{5}$$

$$u_{4x} = \frac{1}{E_2}\left(\frac{\tilde{N}_{\mathrm{L}}}{h_2}x - \frac{6(\tilde{P} - \tilde{F}_{\mathrm{L}})(2L_2x - x^2)z''}{h_2^3}\right) + c_{43}, \quad c \leqslant x \leqslant L_2, \tag{6}$$

where c_{ik} are the unknown constants, $z'' = z + (h_2 + h_{\mathrm{a}})/2$, $z' = z - (h_1 + h_{\mathrm{a}})/2$, $\tilde{N}_{\mathrm{L}} = N_{\mathrm{L}}/G_{\mathrm{a}}$, $\tilde{F}_{\mathrm{L}} = F_{\mathrm{L}}/G_{\mathrm{a}}$ and $\tilde{P} = P/G_{\mathrm{a}}$. The symbols N_{L} and F_{L} denote, respectively, longitudinal and supported forces at the left-end pin support. The subscripts i and k of c_{ik} represent the ith segment of the blue tape and the kth unknown constant.

Similarly, substituting the analytical solutions $\tilde{u}_i$ and equation (1) into equation (2), the transverse and longitudinal displacements of the second and third segments $w_{ix}, \tilde{u}_{ix}$ ($i = 2$ or 3) can also be derived by symbolic manipulation and expressed in terms of c_{ij}, $\bar{\mathrm{S}}$, $\bar{\mathrm{C}}$, $\overline{\mathrm{Ch}}$, $\overline{\mathrm{Sh}}$, $\overline{\mathrm{Ch}}_1$ and $\overline{\mathrm{Sh}}_1$.

The longitudinal displacements u_i and u_{ix} can be derived by substituting the analytical solutions $\tilde{u}_i, \tilde{u}_{ix}, w_i$ and w_{ix} into the integrated equations (7) and (8) and including both the unknown constants, $c_{\mathrm{a}i1}$ and $c_{\mathrm{a}i2}$:

$$\frac{\mathrm{d}^2u_i}{\mathrm{d}x^2} = \frac{12}{E_1^*h_1}\left[-\frac{G_{\mathrm{a}}}{h_{\mathrm{a}}}\left(u_i\left(\frac{h_{\mathrm{a}}}{2}\right) - u_{ix}\left(-\frac{h_{\mathrm{a}}}{2}\right)\right)\right] - z'\frac{\mathrm{d}^3w_i}{\mathrm{d}x^3}, \quad i = 2 \text{ or } 3, \tag{7}$$

$$\frac{\mathrm{d}^2u_{ix}}{\mathrm{d}x^2} = \frac{12}{E_2^*h_2}\left[-\frac{G_{\mathrm{a}}}{h_{\mathrm{a}}}\left(u_i\left(\frac{h_{\mathrm{a}}}{2}\right) - u_{ix}\left(-\frac{h_{\mathrm{a}}}{2}\right)\right)\right] - z''\frac{\mathrm{d}^3w_{ix}}{\mathrm{d}x^3}, \quad i = 2 \text{ or } 3. \tag{8}$$

These variables, which are either functions of both x and z or only a function of x, are expressed as $u_i = u_i(x, z)$, $u_{ix} = u_{ix}(x, z)$, $w_i = w_i(x)$ and $w_{ix} = w_{ix}(x)$ ($i = 2$ or 3). The longitudinal displacement $u_i(h_{\mathrm{a}}/2)$ of the IC chip and the longitudinal displacement $u_{ix}(-h_{\mathrm{a}}/2)$ of the blue tape are then represented as a function of x, and are expressed as either $z = h_{\mathrm{a}}/2$ or $z = -h_{\mathrm{a}}/2$.

To prove whether these analytical solutions are correct, they are once again substituted into the system differential equations, equation (2), which shows c_{i4} and c_{i5} to be equal to zero.

2.2. Relationship Between Displacement and Stress

The adhesive layer's peel and shear stresses, $\sigma_{\mathrm{a}i}$ and $\tau_{\mathrm{a}i}$, respectively, are shown in the following expressions.

When $i = 2$ represents the first segment ($-c \leqslant x \leqslant -d$) of the adhesive layer and $i = 3$ represents its second segment ($-d \leqslant x \leqslant c$),

$$\sigma_{\mathrm{a}i} = E_{\mathrm{a}}\frac{(w_i - w_{ix})}{h_{\mathrm{a}}}, \quad i = 2 \text{ or } 3, \tag{9}$$

$$\tau_{ai} = \frac{G_a(u_i(h_a/2) - u_{ix}(-h_a/2))}{h_a}, \quad i = 2 \text{ or } 3. \tag{10}$$

Similarly, when $i = 2$ represents the first segment ($-c \leqslant x \leqslant -d$) of the IC chip and $i = 3$ represents its second segment ($-d \leqslant x \leqslant c$), the normal stresses of the IC chip and blue tape are expressed as:

$$\sigma_i = \frac{du_i}{dx}, \quad i = 2 \text{ or } 3. \tag{11}$$

When $i = 1, 2, 3$, or 4 represents the first, second, third, or fourth segment of the blue tape, the normal stresses of the blue tape are expressed as:

$$\sigma_{ix} = \frac{du_{ix}}{dx}, \quad i = 1, 2, 3 \text{ or } 4. \tag{12}$$

These stresses, σ_{ai}, τ_{ai}, σ_i and σ_{ix}, can be found by symbolic manipulation and can be expressed in terms of $c_{i4}, c_{i5}, c_{ij}, \overline{\mathrm{S}}, \overline{\mathrm{C}}, \overline{\mathrm{Ch}}, \overline{\mathrm{Sh}}, \overline{\mathrm{Ch}}_1$ and $\overline{\mathrm{Sh}}_1$.

2.3. Nondimensionalization

Some parameters are nondimensionalized, which mainly aims to regulate the magnitude of these parameters and allows numerical results to be obtained with only little likelihood of truncation error (see Table 1). The adhesive layer's nondimensional peel and shear stresses are $\overline{\sigma}_{ai} = 2c\sigma_{ai}/P$ and $\overline{\tau}_{ai} = 2c\tau_{ai}/P$, while the nondimensional normal stresses of the IC chip and blue tape are $\overline{\sigma}_i = 2c\sigma_i/P$ and $\overline{\sigma}_{ix} = 2c\sigma_{ix}/P$, respectively.

2.4. Constraints and Boundary Conditions

At the left-end pin support ($x = -L_1$) of the blue tape, there are two boundary conditions: zero transverse displacement and zero longitudinal displacement of the blue tape. At $x = -c$, there are eight constraints: six are continuity conditions for the blue tape and the remaining two are that both the bending moment and longitudinal force of the IC chip must be equal to zero.

At the junction point ($x = -d$) between the second and third segments, there are eleven conditions, eight of which are continuity conditions. The three other conditions can be written as follows: (i) the total shear force in the left-side neighborhood of junction point ($x = -d^-$) is $\tilde{F}_L/\tilde{P}$, (ii) the total shear force in the right-side neighborhood of junction point ($x = -d^+$) is $(\tilde{F}_L - \tilde{P})/\tilde{P}$ and (iii) the total longitudinal force has the same value at junction point ($x = -d$) for both the second and third segments.

The model also has eight constraints at $x = c$. The junction point ($x = c$) between the third and fourth segments of the blue tape has the same eight constraints as the junction point ($x = -c$) between the first and second segments of the blue tape.

At the right-end pin support ($x = L_2$) of the blue tape, there are again two boundary conditions: both the transverse displacement and longitudinal displacement for the blue tape must be zero.

Table 1.
Nondimensional terms and equations for IC chip, adhesive layer and blue tape [23]

Nondimensional terms	Equation	Nondimensional terms	Equation
For IC chip		For blue tape	
Thickness ratio	$\beta_1 = \frac{h_1}{h_\mathrm{a}}$	Thickness ratio	$\beta_2 = \frac{h_2}{h_\mathrm{a}}$
Thickness to length ratio	$\gamma_1 = \frac{h_1}{2c}$	Thickness to length ratio	$\gamma_2 = \frac{h_2}{2c}$
Elastic modulus	$E_1 = \frac{E_1^*}{G_\mathrm{a}}$	Elastic modulus	$E_2 = \frac{E_2^*}{G_\mathrm{a}}$
Shear force	$\overline{Q}_i = \frac{Q_i}{P}$	Shear force	$\overline{Q}_{ix} = \frac{Q_{ix}}{P}$
Moment	$\overline{M}_i = \frac{M_i}{2Pc}$	Moment	$\overline{M}_{ix} = \frac{M_{ix}}{2Pc}$
Longitudinal force	$\overline{N}_i = \frac{N_i}{P}$	Longitudinal force	$\overline{N}_{ix} = \frac{N_{ix}}{P}$
Normal stress	$\bar{\sigma}_i = \frac{2c\sigma_i}{P}$	Normal stress	$\bar{\sigma}_{ix} = \frac{2c\sigma_{ix}}{P}$
For adhesive layer			
Peel stress	$\bar{\sigma}_{\mathrm{a}i} = \frac{2c\sigma_{\mathrm{a}i}}{P}$		
Shear stress	$\bar{\tau}_{\mathrm{a}i} = \frac{2c\tau_{\mathrm{a}i}}{P}$		
Elastic modulus	$E_0 = \frac{E_\mathrm{a}}{G_\mathrm{a}}$		
x-axis	$\bar{x} = \frac{x}{c}$		

The number of constraints and boundary conditions totals 31, which equals the number of unknown constants. In addition to the unknown constants c_{ij}, $c_{\mathrm{a}i1}$, $c_{\mathrm{a}i2}$, c_{1k}, c_{4k} and N_L, subscript i is equal to 2 or 3, k ranges from 1 to 3 and j from 1 to 12, but c_{i4} and c_{i5} equal zero (explained and described above). The 31 unknown constants can be obtained using Mathematica's SVD algorithm for an inverse matrix, after which these calculations can be carried out in the Mathematica package [25].

2.5. Optimum Design Problem

Although the geometrical shape and properties of the IC chips have already been determined in the IC chip pick-up process experiments, examining factors like the mechanical properties and thickness of the adhesive and the mechanical properties of the blue tape enables analysis of the peel and shear stresses of the adhesive layer and the stresses of the IC chip and blue tape. To carry out such an analysis, this study adopts a genetic algorithm with a penalty function because the geometrical dimensions and material properties of the adhesive, IC chips, and blue tape greatly affect the stress distributions of the adhesively bonded joint in the IC chip pick-up process (see Fig. 11 of Cheng *et al.* [23]). Moreover, choosing the most suitable adhesive from among numerous types is difficult.

Because the Poisson's ratio of plastic materials is usually 0.35–0.4, a middle value of 0.375 for these materials is adopted as the Poisson's ratio of the adhesive. Based on an earlier experimental study [24], in this study, mechanical properties and thickness of adhesive are assumed as design variables converted into two nondimensional parameters. That is, the optimum problem of this study includes two design variables: the elastic ratio λ and the thickness ratio β_1. The elastic ratio λ is defined as the ratio of the IC chip elastic modulus (E_1) to the elastic modulus (E_a) of the adhesive layer; the thickness ratio β_1 is the ratio of the IC chip thickness (h_1) to the thickness (h_a) of the adhesive layer. The cost function and constraint conditions of this optimum design problem are described in the following equations.

The cost function minimizes the von Mises stress of the adhesive layer at both ends of the IC chip and is written as:

$$f(\beta_1, \lambda) = -\sqrt{\bar{\sigma}_{\mathrm{a}i}(\beta_1, \lambda)^2 + 3\bar{\tau}_{\mathrm{a}i}(\beta_1, \lambda)^2}, \quad i = 2, 3. \tag{13}$$

The constraints can then be expressed as follows:

1. The largest value of the IC chip stress is no greater than its allowable stress.
2. The largest value of the blue tape stress is no greater than its allowable stress.
3. The peel stress is a positive value in the adhesive, i.e., the tensile stress.

$$|\overline{\sigma}_i(\beta_1, \lambda)| - \frac{\overline{\sigma}_{ul}}{Fs} \leqslant 0, \quad i = 2, 3, \tag{14}$$

$$|\overline{\sigma}_{ix}(\beta_1, \lambda)| - \frac{\overline{\sigma}_{ypx}}{Fs} \leqslant 0, \quad i = 2, 3, \tag{15}$$

$$-\overline{\sigma}_{\mathrm{a}i}(\beta_1, \lambda) < 0, \quad i = 2, 3. \tag{16}$$

Similarly, the nondimensional critical stresses of the IC chip and blue tape are expressed as $\overline{\sigma}_{ul} = 2c\sigma_{ul}/P$ and $\overline{\sigma}_{ypx} = 2c\sigma_{ypx}/P$, while σ_{ul} and σ_{ypx} depict, respectively, the ultimate stresses of the IC chips and the yield stress of the blue tape.

Expressions (14)–(16) are then rewritten as equations (17)–(19):

$$g_1(\beta_1, \lambda) = \frac{|\overline{\sigma}_i|Fs}{\overline{\sigma}_{ul}} - 1 \leqslant 0, \tag{17}$$

$$g_2(\beta_1, \lambda) = \frac{|\overline{\sigma}_{ix}|Fs}{\overline{\sigma}_{ypx}} - 1 \leqslant 0, \tag{18}$$

$$g_3(\beta_1, \lambda) = -\overline{\sigma}_{ai} < 0. \tag{19}$$

The values of the material constants and of the parameters listed in Table 2 are used in the numerical solution. Given the cost values involved, particularly the high variation near both ends of the IC chip, the search for the optimum solution employs

Table 2.
Mechanical properties and dimensions for IC chip and blue tape [24, 31]

Material	Elastic modulus (Pa)	Poisson's ratio	Thickness (mm)	Critical stress (yield stress or ultimate strength)	Dimension
IC chip (silicon)	1.29×10^{11}	0.28	0.1 or 0.34	130 MPa	5×5 mm (square)
Blue tape UE-1085GX*	3×10^{9}	0.38	0.07	30 MPa	$r = 150$ mm (radius)
Adhesive (radiation-cured)	–	0.375	0.01	5.9 MPa (before UV) 1.45 MPa (after UV)	–

* A product of Nitto Denko Corporation [31].
– Not available.

the C++ program of the genetic algorithm, which has been modified from M.I.T.'s (Massachusetts Institute of Technology) C++ source [28] to incorporate a penalty function [27]. This program of genetic algorithm associated with adhesively bonded joint analysis is applied to the search for the properties of adhesive and blue tape. The adhesively bonded joint analysis is obtained through the Mathematica package and is used to compute the stresses including the normal stresses of the IC chip and blue tape and the peel and shear stresses of the adhesive layer. The penalty function is expressed as:

$$P(R, \beta_1, \lambda) = \sum_{1}^{3} R|g_i(\beta_1, \lambda)| \quad \text{if } g_i(\beta_1, \lambda) > 0, \tag{20}$$

where R is the penalty parameter. Because the optimization program using the genetic algorithm incorporates constraints, the original minimization of the cost function f (the von Mises stress of the adhesive layer) is modified as follows:

$$F = f + P. \tag{21}$$

The genetic algorithm of this problem, written in C++ language, uses a roulette wheel scheme and encodes the design variable values into 16 binaries [26]. The flow chart for its calculation process, shown in Fig. 2, is described in more detail and illustrated below.

First, the values of populations are randomly generated and given to both the thickness and elastic ratios (β_1 and λ) used to calculate the normal stresses of the IC chip and blue tape and the von Mises stress of the adhesive layer in the Mathematica package. Next, the genetic algorithm program reads the values of these stresses to computer cost function F (with a penalty function), whose values are then used to determine gene fitness and test the convergence criterion. If the results

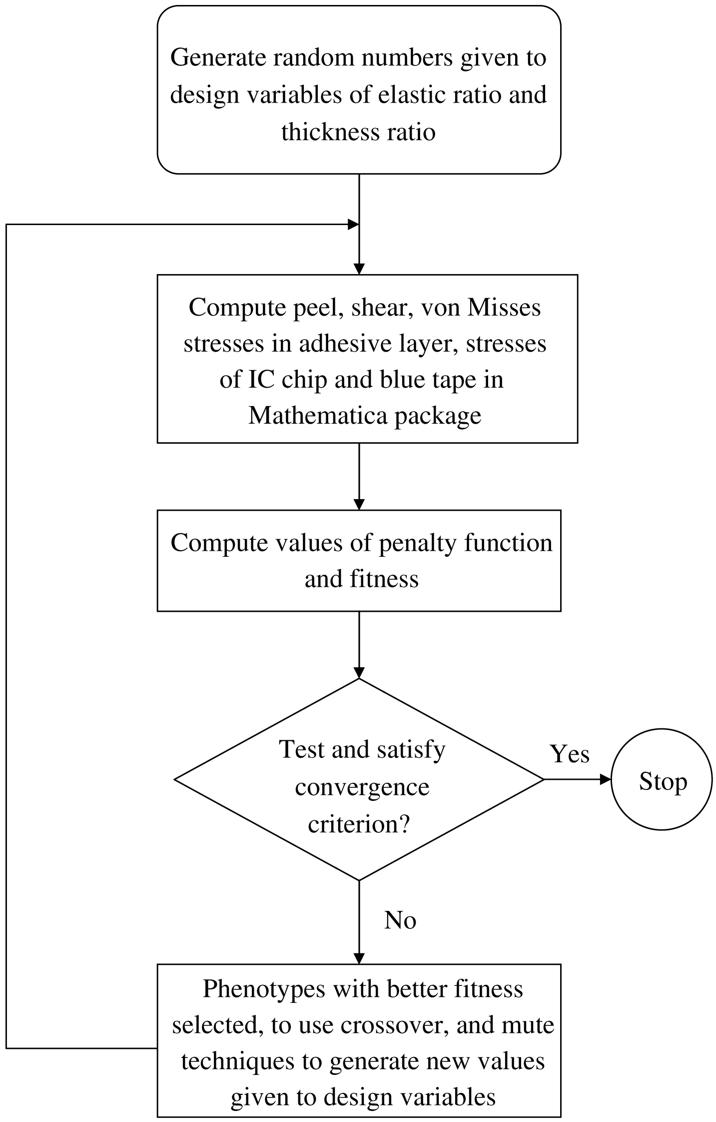

Figure 2. Flow chart of genetic algorithm, associated with adhesively bonded joint analysis, used to compute stresses in the adhesive, stresses of IC chip and blue tape through Mathematica package.

satisfy the convergence criterion, the program is normally ended; however, if no satisfactory result is achieved, the remaining phenotypes with better fitness values are selected to generate new populations using crossover and mute techniques [26], and subsequently, the calculation returns again to the second block where the stresses of IC chip, blue tape and the adhesive layer are computed.

Some genetic algorithm parameters include a penalty parameter, 10^{11}, a crossover probability of 0.6 or 0.8, a mute probability of 0.01, and a population size of 50 or 100 generations [21]. However, on a Duo-Core T2300 PC computer with a 512 Mbyte RAM and a 1.6 GMz CPU, such a program is quite time consuming, taking about 16–30 h. Therefore, here we adopted the Multifunctional Optimization System Tool (MOST) software designed by Tseng [29], which allows simultaneous examination of the genetic algorithm results. Generally, it can be difficult to find optimum solutions to a problem that is so sensitive to initial design values, side constraints (ranges of design variables), and the first-order derivations having large values for design variables.

3. Results and Discussion

Three cases are discussed below. Case A analyzes and discusses the failure during the pick-up process of IC chips having a thickness of 0.1 mm and a length of 5 mm [24]. Case B investigates the pick-up process for IC chips with a thickness of 0.34 mm and a length of 5 mm, and Case C discusses ways to improve the success rate of Case A.

3.1. Case A: Analysis of IC Chips With 0.1 mm Thickness and 5 mm Length

Some data required by this analysis of the failure of IC chips having a 0.1 mm thickness and a 5 mm length are adopted from Cheng *et al.* [24]. The relevant mechanical properties and geometrical dimensions are listed in Table 2, which shows the critical stresses of the IC chip, blue tape, and adhesive to be 130, 30 and 1.45 MPa (after exposure to UV light), respectively. The thickness of the adhesive layer is 0.01 mm, the concentrated force is 4.8 N, and the safety factor is 1.1.

A search for the elastic modulus of the adhesive layer reveals a range from one hundred times to one-fiftieth that of the IC chip (i.e., the side constraints are $0.01 \leqslant \lambda \leqslant 50$ or the elastic modulus of the adhesive layer varies from 1.29×10^{13} Pa to 2.58×10^{9} Pa). For an adhesive layer thickness of 0.01 mm, the genetic algorithm is employed only to search for the layer elastic modulus: it produces no solution for the modulus nor satisfies constraints. In other words, even though the adhesive layer's elastic modulus varies within the above-described range, the IC chip with a 0.1 mm thickness still fails in the IC chip pick-up process because the adhesively bonded joint has the maximum von Mises stress in the center of its adhesive layer [24].

Based on the expectation that the success rate of the IC pick-up process can be enhanced by varying the adhesive thickness, the genetic algorithm is used to search for two variables: the elastic modulus and the thickness of the adhesive layer. The elastic modulus search still is in the above-described range, while the adhesive layer thickness search reveals a range from one time to one-fiftieth that of the IC chip (i.e., $1 \leqslant \beta_1 \leqslant 50$ or an adhesive layer thickness that varies from 0.1 to 0.002 mm). However, running more than 10 reiterations of a genetic algorithm search for the side constraint ranges produces no solutions for the elastic modulus and the adhesive layer thickness in satisfaction of the constraints. Therefore, in such a situation, it is almost impossible to fully separate the IC chips from the blue tape without breakage. Rather, because the maximum von Mises stress occurs in the center of the adhesive layer, the result is the same as described in the preceding discussion (about the adhesive layer thickness of 0.01 mm) in Case A.

3.2. Case B: Analysis of IC Chips With 0.34 mm Thickness and 5 mm Length

For Case B, the parameter values and mechanical properties are the same as those for Case A except for an IC chip thickness of 0.34 mm and a concentrated force of 3.5 N [24]. Again, because the thickness of the adhesive layer is 0.34 mm, the genetic algorithm is only employed to search for the layer's elastic modulus with the same range as Case A. The search for the von Mises stress reveals it to be 4.05 MPa, which is greater than the 1.45 MPa critical stress (after exposure to UV light) of radiation-cured adhesive listed in Table 2. To satisfy the constraints, the solution for the adhesive layer's elastic modulus is 2.46×10^{10} Pa when the optimum value of the adhesive layer's von Mises stress is 4.05 MPa. Moreover, the adhesively bonded joint has maximum von Mises stress at both ends.

Based on the expectation that general types of adhesives can be used in the IC pick-up process, the genetic algorithm was also employed to search for the adhesive layer's elastic modulus and thickness within the ranges of 1.29×10^{11} Pa to 2.58×10^{9} Pa and 0.1 mm to 0.002 mm, respectively (i.e., with side constraints of $1 \leqslant \lambda \leqslant 50$ and $1 \leqslant \beta_1 \leqslant 50$). The results show the elastic modulus and adhesive layer thickness to be 2.77×10^{10} Pa and 0.027 mm, respectively. This search also reveals that the optimum value of the adhesive layer's von Mises stress is 352 MPa, which far exceeds the critical value of general types of adhesives (40–80 MPa) [30]. Thus, given the constraints and the von Mises stress, it is extremely probable that the IC chips can be successfully and entirely separated from the blue tape without failure. Again, the adhesively bonded joint has maximum von Mises stress at both ends.

3.3. Case C: Effects of Elastic Moduli of the Blue Tape and Adhesive Layer on IC Chip Stresses (IC Chips Given 0.1 m Thickness and 5 mm Length)

According to Case A, IC chips fail easily during the IC chip pick-up process. Therefore, improving the success rate of Case A requires consideration of various mechanical properties of both the adhesive layer and blue tape. First, in Case A, as the adhesive's elastic modulus and thickness vary within two specified ranges described above (i.e., $0.01 \leqslant \lambda \leqslant 50$ and $1 \leqslant \beta_1 \leqslant 50$), no solutions for either the adhesive layer modulus or thickness are found. However, the blue tape's elastic modulus increases discretely from one-twentieth to one-fifth, one-tenth, one time, five times, ten times, twenty times and forty-three times that of IC chips, while the adhesive's elastic modulus changes within the above-specified range (i.e., $0.01 \leqslant \lambda \leqslant 50$). On the other hand, the search range of the adhesive thickness — from 0.1 to 0.002 mm — remains unchanged. The optimum values of the von Mises stresses and the values of the adhesive's elastic modulus and thickness are listed in Table 3.

Table 3.
Optimum points and values of adhesive for various elastic moduli of blue tape (E_2) with 0.07 mm thickness

Elastic modulus of blue tape (E_2) (Pa)	Ratio of E_2 to E_1	Elastic modulus of adhesive (Pa)	Thickness of adhesive (mm)	Optimum value (von Mises stress) (MPa)
3.0×10^9	1/43.3	–	–	–
6.45×10^9	1/20	–	–	–
8.6×10^9	1/15	6.47×10^{11}	0.097	44.5
1.29×10^{10}	1/10	2.51×10^{12}	0.007	138.2
2.58×10^{10}	1/5	1.08×10^{12}	0.01	157.8
1.29×10^{11}	1	2.06×10^{11}	0.011	218.5
6.45×10^{11}	5	1.17×10^{13}	0.095	334.4
1.29×10^{12}	10	1.20×10^{13}	0.093	329.7
1.935×10^{12}	15	1.27×10^{13}	0.081	474.3
2.58×10^{12}	20	2.13×10^{12}	0.005	464.6
5.55×10^{12}	43.3	1.01×10^{11}	0.003	334.1

Elastic modulus of IC chip ($E_1 = 1.29 \times 10^{11}$ Pa).
Search ranges:
2.58×10^9 Pa $\leqslant$ elastic modulus of adhesive $\leqslant 1.29 \times 10^{13}$ Pa,
0.002 mm $\leqslant$ thickness of adhesive $\leqslant$ 0.1 mm.
– Not available.

Given the blue tape's elastic modulus of 3.0×10^9 Pa and 6.45×10^9 Pa (i.e., a 1/43.3 or 1/20 ratio of the blue tape elastic modulus to the IC chip elastic modulus), about ten search reiterations were run within the ranges of the adhesive's elastic modulus and thickness; however, no solutions were obtained in satisfaction of the previously mentioned constraints. Nevertheless, as the blue tape's elastic modulus increases to higher than 8.6×10^9 Pa (i.e., a ratio greater than 1/15), the adhesive's elastic modulus and thickness can be found using the genetic algorithm under the constraints. As the blue tape's modulus is only 8.6×10^9 Pa, the von Mises stress value (44.45 MPa) is less than 100 MPa (general types of adhesives having the critical value of 40–80 MPa [30]), while the other values are greater than 130 MPa. The adhesive's elastic modulus ranges from 9×10^{13} Pa to 10^{11} Pa. As a result, because the blue tape's elastic modulus is greater than one-tenth that of the IC chips and the von Mises stress values are greater than 130 MPa, the probability of the IC chips being fully separated from the blue tape can be raised.

4. Conclusions

The experiments revealed that given an IC chip thickness and length of 0.1 and 5 mm, respectively, the chips not separated from the blue tape are likely to fail in the IC pick-up process even though they are subjected to a force which is increased to 4.8 N. For the analytical model, the genetic algorithm, associated with adhesive joint analysis to investigate the stress distributions of the adhesive as well as the stresses of IC chips and blue tape, is applied to search for the adhesive layer's elastic modulus or its thickness. In accordance with the experimental results, this search produced no solutions for either the adhesive layer's elastic modulus or its thickness.

When the IC chip thickness was increased to 0.34 mm and the chips were subjected to a 3.5 N force, the optimum value of the layer's von Mises stress in the adhesive layer far exceeds the adhesive's critical values. Based on the experimental results, it is extremely possible that IC chips can be successfully and fully separated from the blue tape without breakage. Moreover, as analysis of different IC chip thicknesses reveals that the maximum von Mises stress occurs either in the center or at both ends of the adhesive layer, whether or not the IC chips can be successfully picked up can be determined from the location of this stress.

Since it is apparent that an IC chip of 0.1 mm thickness subjected to a force of 4.8 N can easily fail, the findings of this study are expected to improve the success rate of the IC chip pick-up process. Specifically, when the blue tape's elastic modulus is greater than one-tenth that of the IC chips, the success rate increases. As the von Mises stress of the adhesive layer, being greater than 130 MPa, exceeds the adhesive's critical value (40–80 MPa) [30], the probability of the IC chips being fully separated from the blue tape without breaking is expected to increase.

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