Research Based on Cohesive Zone Model for Interface Delamination of Waste Plastic Chip

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Abstract. The interface delamination of waste plastic chip will seriously affect the value of their recycling reuse; therefore, it has been a hot issue in recycling researches of Waste Electrical and Electronic Equipment (WEEE). Based on the exponential cohesion theory, this paper has researched chip delamination and established the Cohesive Zone Model (CZM) of delamination crack for chip interface, as well as proposed a method which combined the experiment of crack surface observation and the simulation of fracture mechanics. By employing this method, the CZM parameters of waste plastic chip interface have been obtained. Based on the CZM, the simulation of waste plastic chip interface delamination has been made, and its results showed that: temperature and humidity factors have a significant impact on the chip delamination. At last, the disassembly experiments of Waste Printed Circuit Boards (WPCB) have been made under different disassembly technology, and the delamination rate of resulting chips has been calculated. Then this paper has analyzed the influence rule of different disassembly conditions on the chip delamination and verified the correctness of chip delamination simulation results, as well as proposed an optimized disassembly technology of WPCB for reducing plastic chip's delamination.

Introduction

With the rapid development of world economy, a large number of Waste Electrical and Electronic Equipment (WEEE) appeared each year, and caused tremendous pressure to the environment, then the recycling of WEEE has become a major issues causing social attention. Countries all around the world have issued corresponding bill about WEEE processing [1]. For example, the WEEE Directive issued by European Union in 2003 cleared rules for ten classes of recovery and regeneration utilization of WEEE. Printed Circuit Board (PCB) is the important material for classification processing after dismantling the WEEE, "the National Hazardous Waste List" of China clearly stipulates that PCB components are T-class hazardous wastes. Therefore, studying the recycling method is of great significance. Component reuse is an effective method to achieve the high value recycling of Waste Printed Circuit Boards (WPCB), and is the current hot research spot.

Study shows that the design life of components is 500000 hours, while the average service life of WEEE in developed country is only 20000 hours. According to the Bathtub Curve theory of components invalidation, the component is in the optimal period of quality, and has high reuse value [2]. Guo Xiuying et al.[3,4] researched the reusability of waste plastic chip through experimental method in 2009, then put forward that the qualified rate can be up to 98% as long as the recycling way of waste plastic chip is reasonable and normative, and it could make very high reuse value. The delamination damage of waste plastic chip is a common problem which influences chips' reuse value and reliability, so the research of chip interface delamination has been the core content in the waste plastic chip reusability study.

Aiming at the interface delamination fracture problems of waste plastic chip, the exponential Cohesive Zone Model (CZM) was used to analyze delamination crack of two phase interface in chip interior, and the chip interface delamination was analyzed by adopting finite element simulation method with the CZM as a guide. Finally, the simulation results were verified to be

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effective through the WPCB disassembly experiment, and concrete countermeasures of WPCB disassembly technology to reduce the chip delamination were put forward.

The Cohesive Zone Model

Traditional interface delamination fracture research was conducted using fracture mechanics simulation method, thus it needed to set the preset crack in simulation model. Due to the position and size of preset crack were set subjectively, it often brought great influence on the accuracy of calculation results [5]. In addition, we can also use the cohesion theory to describe the fracture behavior of material. The crack formation and extension phenomenon is analyzed with the tension displacement law of cohesion theory, and it doesn't need preset crack in simulation process, so this is very suitable for the fracture problems of fixed crack propagation path[6]. The delamination phenomenon of plastic chip mainly occurs in the interface between different materials, and the crack formation and extension path is relatively stationary. Therefore, the cohesion theory method was adopted to study the delamination fracture problems of plastic chip in this paper.

In the delamination fracture process of plastic chip, a transition zone generates in the interface between two phase materials. This paper used the edge-opened crack as example to study the fracture process, as shown in Fig.1(a). There is a transition zone between the original interface and free surface in the tensile fracture zone, which is called cohesive zone. The mechanical properties of material in cohesive zone are different from other interfaces of plastic chip. For the mechanical properties of cohesive zone, it is described with the tension displacement law. Among numerous cohesion models, the tension displacement law of exponential CZM most conforms to the Van Der Waals force form, and gets high accuracy to solve the problems of composite interface fracture [7, 8]. So the exponential CZM was adopted to study the interface delamination fracture problems of plastic chip in this paper.

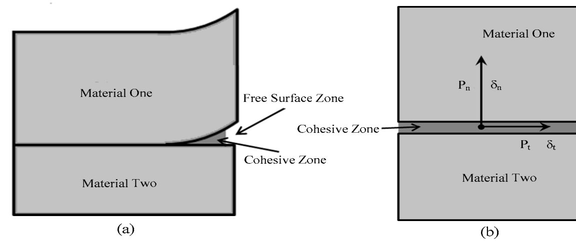


Fig.1 Cohesive zone of plastic chip delamination interface

The cohesive zone of delamination crack in plastic chip is shown in Fig.1(b), making an analysis of one point in the cohesive zone, the received tension of the point can be decomposed to a normal tension P_n which is perpendicular to the interface and a tangential tension P_t which is parallel to the interface. The interface's fracture displacement δ can be also decomposed to a normal displacement δ_n and a tangential displacement δ_t. The relation between the fracture energy $\varphi(\delta)$ of exponential CZM and the interface's fracture displacement δ is shown in Eq.1[8].

$$\varphi(\delta) = e\sigma_{\max}\delta_{t\max}[1-(1+\frac{\delta_n}{\delta_{t\max}})e^{\frac{-\delta_n}{\delta_{t\max}}}e^{\frac{-\delta_t^2}{2\delta_{n\max}^2}}] \tag{1}$$

In formula (1), e is the base of natural logarithms, $\sigma_{\max}$ is the biggest value for the normal tension P_n of the cohesive zone, $\delta_{n\max}$ is the corresponding normal displacement under the action of the maximum normal tension $\sigma_{\max}$, $\delta_{t\max}$ is the corresponding tangential displacement under the action of the maximum tangential tension $\tau_{\max}$.

After getting the partial derivative of fracture energy $\varphi(\delta)$ to normal displacement δ_n, the relation between the normal tension P_n and the normal displacement δ_n is shown in Eq.2.

$$p_n(\delta_n) = \frac{e\sigma_{\max}\delta_n}{\delta_{t\max}}e^{\frac{-\delta_n}{\delta_{t\max}}}e^{\frac{-\delta_t^2}{2\delta_{n\max}^2}} \tag{2}$$

Similarly, after getting the partial derivative of fracture energy $\varphi(\delta)$ to tangential displacement δ_t,

the relation between the tangential tension P_t and the tangential displacement δ_t is shown in Eq.3.

$$p_t(\delta_t) = \frac{e\sigma_{\max}\delta_t}{\delta_{n\max}^2}(\delta_{t\max} + \delta_n)e^{\frac{-\delta_n}{\delta_{t\max}}}e^{\frac{-\delta_t^2}{2\delta_{n\max}^2}} \tag{3}$$

In the delamination fracture process of plastic chip, it is assumed that tangential displacement $\delta_t \to 0$, normal displacement $\delta_n \to \infty$. According to the Eq.1, the fracture energy Ψ_n for getting interface fracture of plastic chip in normal direction is shown in Eq.4.

$$\psi_n = e\sigma_{\max}\delta_{t\max} \tag{4}$$

Similarly, it is assumed that normal displacement $\delta_n \to 0$, tangential displacement $\delta_n \to \infty$. The fracture energy Ψ_t for getting interface fracture of plastic chip in tangential direction is shown in Eq.5.

$$\psi_t = e\sigma_{\max}\delta_{t\max} \tag{5}$$

According to the Eq.4 and Eq.5, occurring interface fracture of plastic chip in normal direction and tangential direction requires the same fracture energy.

It is assumed that normal displacement δ_n=0, tangential displacement $\delta_t = \delta_{t\max}$. According to the Eq.3, the maximum tangential tension $\tau_{\max}$ is shown in Eq.6.

$$\tau_{\max} = \sqrt{e}\sigma_{\max}\frac{\delta_{t\max}}{\delta_{n\max}} \tag{6}$$

Research shows that the main force causing interface delamination of plastic chips is interfacial shear [9], so this paper focused on the use of *tangential tension-displacement* (P_t - δ_t) formula to simulate the delamination phenomenon of plastic chips. According to the Eq.3, making normal displacement δ_n=0, the relation between the normalization tangential tension $\Pi_p = P_t/\tau_{\max}$ and the normalization tangential displacement $\Delta_\tau = \delta_t / \sqrt{2}\delta_{n\max}$ is shown in Eq.7.

$$\Pi_p(\Delta_\tau) = \sqrt{2e}\Delta_\tau e^{-\Delta_\tau^2} \tag{7}$$

The curve of Eq.7 is shown in Fig.2. It shows that when $\Delta_\tau = \sqrt{2}/2$, namely $\delta_t = \delta_{n\max}$, the tangential tension of cohesive zone reaches the maximum value $\tau_{\max}$, then with the tangential displacement Δ_τ increasing, interface delamination fracture of plastic chip will occur. When $\Delta_\tau = 3\sqrt{2}/2$, namely $\delta_t = 3\delta_{n\max}$, the tangential tension P_t of cohesive zone decreases to approximately 5% of maximum tangential tension $\tau_{\max}$, the interface of plastic chip is almost completely fractured at this time, and it is serious delamination damage to plastic chip.

Above is the exponential cohesion mathematical model. For the interface delamination fracture problems of plastic chips, when material interface is different, the parameters of CZM and the *tension-displacement* curve is also different. Thus, for a particular delamination interface of plastic chips, which should have the only parameters of CZM, i.e., the fracture energy ($\Psi_n = \Psi_t$) and the displacement ($\delta_{n\max}$, $\delta_{t\max}$) under the action of maximum tension in all directions are uniquely determinate. In the actual analysis of the plastic chips' delamination crack, the parameters of CZM should be calculated beforehand depending on the mechanical properties of interface two-phase material in plastic chip. Then the resulting model parameters are substituted into the CZM, and the next step of delamination simulation is following.

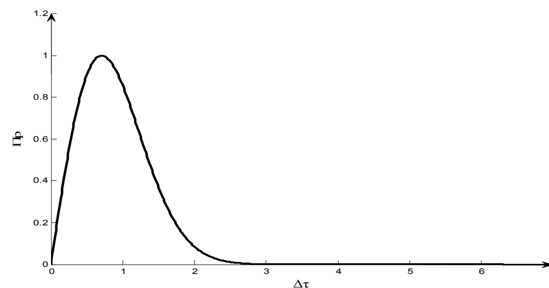


Fig.2 Relation curve of tangential tension Π_p and tangential displacement Δ_τ

Experimental Determinations for Parameters of Cohesive Zone Model

Prior to the delamination simulation of plastic chip by CZM, the model parameters for corresponding interface of plastic chip should be obtained. A combination of experiments and simulation methods were adopted to determine the model parameters in this paper, which was shown in Fig.3. The fracture displacement parameters of CZM can be obtained through the crack observation experiment. The fracture energy parameters of CZM can be obtained through the method of combining strength test and crack propagation simulation.

The *substrate-molded plastic* interface of old Quad Flat Pack (QFP) plastic chip was used as the measuring object in this paper, and the following parameters were measured separately.

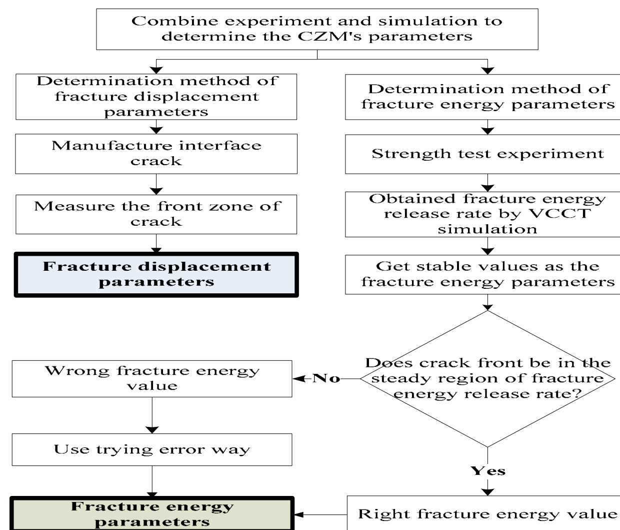


Fig.3 Determination process of Cohesive Zone Model's parameters

The Interface Fracture Displacement Parameters of Plastic Chips

The fracture displacement parameters were measured by the method of manually manufacturing and measuring interface cracks of plastic chips. Due to the width magnitude of the interface crack is 1μm, it cannot be measured with the naked eyes, so a scanning electron microscope is necessary to realize the observations and measurement. Strong thermal shock was formed in the interface by applying high temperature load to the old plastic chips, and the minor cracks were produced due to the different thermal expansion coefficients of the two-phase materials at chips' interfaces. Then the processing of cutting, grinding, polishing etc. were done to the chips, and the electron microscopy sections perpendicular to the direction of interface were produced. Finally, a scanning electron microscopy was used to measure the front zone of minor crack to get the fracture displacement. As shown in Fig.4, the maximum normal fracture displacement $\delta_{n\max}$ of *substrate - molding plastic* interface is 0.0003mm, so the maximum tangential fracture displacement $\delta_{t\max}$ is also 0.0003mm. Thereby the corresponding fracture displacement parameters of CZM for the old QFP plastic chip's *substrate-molded plastic* interface were obtained.

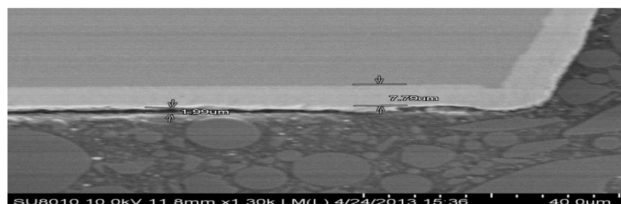


Fig.4 Front zone of *substrate-molded plastic* interface crack

The Fracture Energy Parameters

For the interfacial fracture energy parameters of old plastic chips, firstly the shear strength of *substrate-molded plastic* interface was obtained by strength test experiment, then the shear strength values were loaded as the boundary conditions of finite element simulation, and the interfacial fracture energy parameters for old plastic chips were obtained through the pre-crack simulation method. In order to accurately measure the shear strength of *substrate - molding plastic* interface,

the excess parts of the chip were processed by small feed rate intermittent grinding, and the junction surface between the molded plastic and substrate was exposed. In the experiment, one side of the experimental sample's junction surface was fixed, and junction surface of the other end was cut by cutting head, as shown in Fig.5(a). The shear test device was shown in Fig.5(b). The stress-rupture curve of *substrate-molded plastic* interface was shown in Fig.6, it showed that the fracture behavior of *substrate-molded plastic* interface occurred instantaneously, and no material yield process happened, which meant to be brittle fracture. In experimental process, several groups of data were measured, and it showed that the results' distribution was dispersive. So the average value of several data groups was taken as the final result, and the average shear strength of *substrate-molded plastic* interface was approximately 0.98MPa.

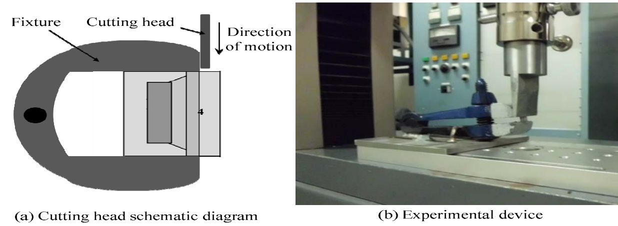


Fig.5 Plastic chip shear test experimental device

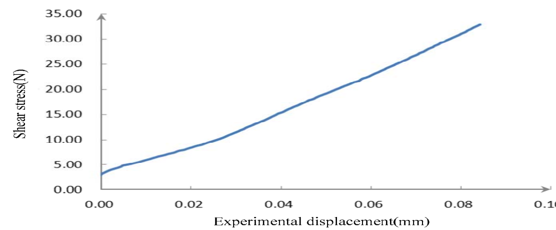


Fig.6 Stress-rupture curve of substrate-molded plastic interface

According to the average shear strength of *substrate-molded plastic* interface obtained in the experiment, the fracture energy release rate under different preset crack length was calculated by ansys13.0 based on Virtual Crack Closure Technique (VCCT). Finite element simulation model is shown in Fig.7, the upper material is molded plastic, and the lower material is copper substrate. The boundary conditions and loads of simulation were set accordance with the shear experiment, the simulation parameters of various materials were as shown below, elastic modulus of molded plastic E_1 = 16 GPa, Poisson's ratio γ_1 = 0.3, elastic modulus of copper substrate E_2 = 120 GPa, Poisson's ratio γ_2 = 0.34. In the simulation, under the effect of maximum shear stress, the relation curve between preset crack length and fracture energy release rate for crack expansion is shown in Fig.8. When preset crack length is greater than 0.5 mm, the fracture energy release rate for crack extension tends to a stable value, and the cohesive zone of preset crack has occurred fracture. At this point the crack front is in steady region of energy release rate, so the stable value of fracture energy release rate is the old chip's *substrate-molded plastic* interface fracture energy Ψ_n=Ψ_t=0.94 J/m2.

Thereby all the necessary parameters of CZM were obtained, after substituting the above parameters into the model, the next step was delamination simulation of plastic chip.

Fig.7 Finite Element Simulation Model

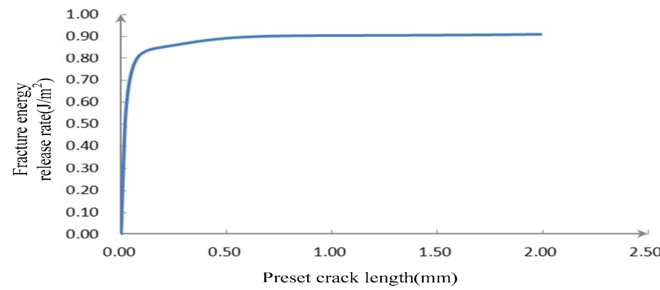


Fig.8 Relation curve of preset crack length and the fracture energy release rate

Delamination Simulations of Plastic Chips

The main factors affecting the interface delamination of old plastic chips included chip's internal structure, material's physical property parameters, temperature and humidity in chip's external environment, and interface strength of chip. Therefore, in order to minimize the error between the analog value and the true value, this paper considered all the factors in the simulation. Due to the structure of plastic chip is symmetrical, the simulation model just needs to create a half of two-dimensional structure. In order to improve the efficiency of simulation, the model omits the pin portion of chip edge. Each component material's physical property parameters of simulation model are shown in Table1.

Table1 Simulation parameters of materials

Material	Modulus of elasticity (MPa)	Poisson's ratio	Thermal expansion coefficient (10^{-6})	Moisture strain ε_H
Molded plastic	16000	0.3	76	0.00702
Copper substrate	120000	0.34	16.9	0
Die	169500	0.278	3.4	0
Die attach	8960	0.25	41	0

After establishing the simulation structural model, based on the corresponding CZM parameters of old QFP plastic chip's *substrate-molded plastic* interface previously acquired above, added the CZM units to all the interfaces of two-phase material in the chip model. The added CZM parameters included normal (tangential) fracture energy 0.94J/m^2, normal fracture displacement 0.0003mm, and tangential fracture displacement 0.0003mm. The resulting two-dimensional mesh model is shown in Fig.9.

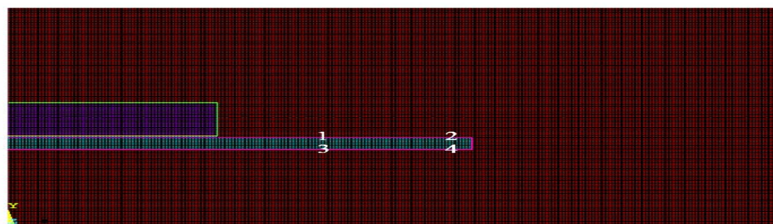


Fig.9 Finite element mesh model of plastic chip

Aim at the main factors affecting the interface delamination of plastic chips, this paper designed comparative simulation groups under different temperatures (A: 200℃, B: 260℃) and different humidity (C: indoor humidity, D: 85℃85% RH environment moisture absorption 168h) conditions. In the simulation process, the fracture displacements of four locations (Zone1~4) marked in the old plastic chip's *substrate-molded plastic* interface (as shown in Figure9) were mainly observed. The fracture simulation is shown in Fig.10, it is for experimental group B-C which is similar to the rest of experimental groups, so this paper no longer enumerates others. The obtained simulation results are shown in Table2, comparing the simulation results in each group, when the chips were in the conditions of high temperature 260℃ or 85℃85%RH environmental conditions moisture

absorption 168h, the chips' interfaces completely occurred delamination phenomenon. The results indicated that the heating temperature and ambient humidity of old plastic chips seriously affected their internal interfaces delamination, so it's necessary to reduce the heating temperature as much as possible in the process of waste PCB disassembly for components reuse. Meanwhile, prior to the PCB disassembly, to reduce the delamination rate of plastic chips in waste PCB disassembly experiment as much as possible, the boards should be roasted and be processed by air drying to remove the absorbing moisture in plastic chips' interior.

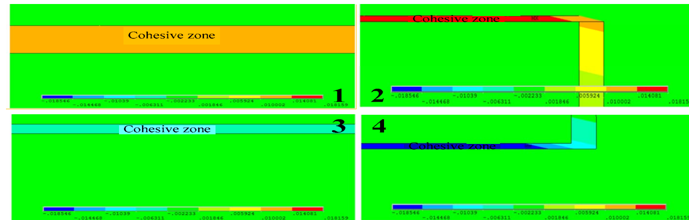


Fig.10 Fracture simulation results of four locations (group B-C)

Table2 Simulation results of comparing experiment groups

Location number	Group A-C		Group B-C		Group A-D		Group B-D	
	Fracture displacement	Delamination	Fracture displacement	Delamination	Fracture displacement	Delamination	Fracture displacement	Delamination
1	0.479	-	100	+	170	+	148	+
2	2.85	-	140	+	240	+	351	+
3	1.31	-	63	+	170	+	155	+
4	2.97	-	180	+	320	+	460	+

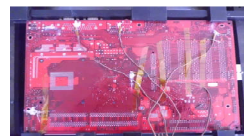
Annotation: fracture displacement unit (10^{-4}mm); '+' means appearing delamination; '-' means no delamination.

Disassembly Experiments of Waste Printed Circuit Boards

According to the results analysis of old plastic chip delamination simulation, in order to get better WPCB disassembly technology, we use self-developed WPCB disassembly equipment to dismantle a number of discarded computer motherboards, which were divided into four groups of comparison experiments. The equipment is shown in Fig.11(a).

(a) WPCB disassembly equipment

(b) Vacuum oven



(c) Collect the surface temperature of PCB

Fig.11 Disassembly experiment equipment

The four groups of WPCB disassembly comparative experiments were as follows: 1) The original group, selected 15 untreated WPCB and used the way of cutting pins to dismantling the old plastic chips on the boards. 2) The low temperature group, selected 15 untreated WPCB and dismantled them at the temperature of 200℃. 3) The high temperature group, selected 15 untreated WPCB and dismantled them at the temperature of 220℃. 4) The pre-baking group, selected 15 untreated WPCB and dried them in a 85℃ vacuum oven (as shown in Fig.11(b)) for 48h, then took them out and dismantled them immediately at the temperature of 200℃. Due to the disassembly equipment's

preset temperature was different from the PCB's surface temperature during the experiment, to real-time monitor the changes of PCB's surface temperature, an eight-channel temperature collection module was used to track and collect the temperature of eight points at upside and downside board ,as shown in Fig.11(c). The PCB's surface temperature in dismantling process was shown in Fig.12.

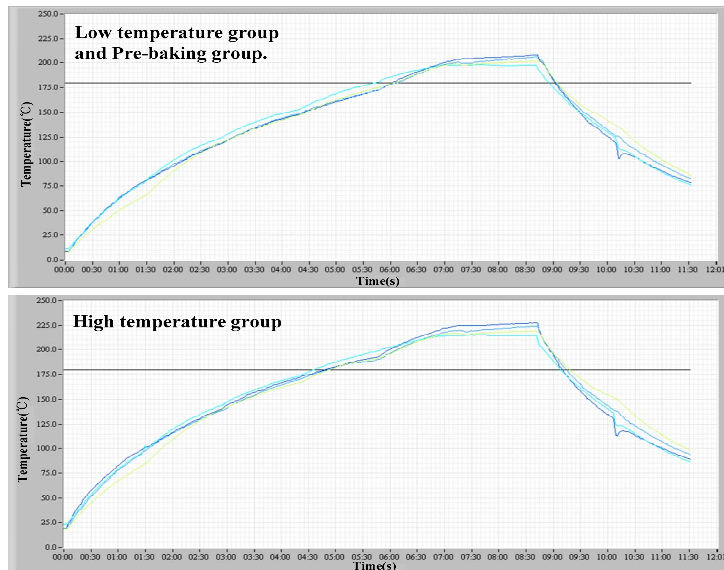
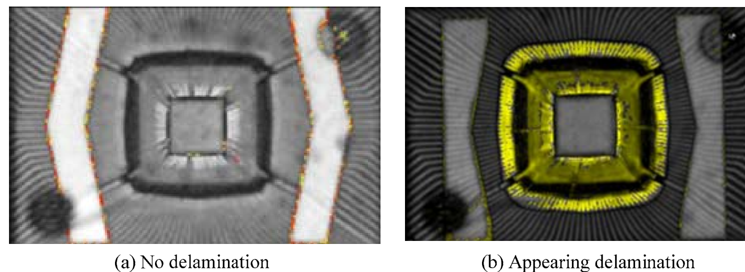


Fig.12 PCB surface temperature monitoring curves in dismantling process

Marked the waste plastic chips dismantled from above four groups of WPCB disassembly experiments, and used the ultrasound C-scan imaging method for detecting delamination morphology of chips' interfaces to determine whether delamination occurred. The ultrasound C-scan images of chips in the experiments were shown in Figure13, the Fig.13(a) was corresponding to plastic chips that interface delamination didn't occur, and Fig.13(b) was corresponding to plastic chips that interface delamination occurred.



(a) No delamination (b) Appearing delamination

Fig.13 Ultrasound C-scan images of old QFP chips

Chip delamination statistics results for the four groups of WPCB disassembly experiments were shown in Table3. From the statistical results, the delamination rate of plastic chips in original group was low to 7.8%, which represented the delamination rate of old plastic chips before dismantling. The delamination rate of plastic chips in low temperature group was 10.6%, which indicated that the delamination rate increased by 2.8% comparing to the delamination rate before dismantling at the temperature of 200℃. The delamination rate of plastic chips in high temperature group was 14%, which increased by 3.4% than the low temperature group. The delamination rate of plastic chips in pre-baking group was 10.4%, which slightly decreased by 0.2% than the low temperature group. The results showed that, for the WPCB long-term storage in a dry room, due to the amount of moisture absorption was small, pre-baking process did not play a significant role in the impact of delamination rate. Thus in actual industrial operations, in order to save the cost of dismantling, we should depend on the environment around WPCB to determine whether it is necessary to add the pre-baking process. The dismantling temperature had a great impact on the delamination of old plastic chips, so in the premise of ensuring the dismantling rate, dismantling temperature should be

lowered to reduce the delamination of plastic chips, like this can achieve WPCB's high value recycling for components reuse.

Table3 Delamination statistics results of chips

Experiment Group	Chip Type	Quantity	Average Delamination Rate
Original group	QFP、PLCC、SOP	51	7.8%
Low temperature group	QFP、PLCC、SOP	47	10.6%
High temperature group	QFP、PLCC、SOP	50	14%
Pre-baking group	QFP、PLCC、SOP	48	10.4%

Conclusions

This paper studied the delamination problems of chips in the waste plastic chips reuse technology research, built the CZM of delamination crack, and obtained the parameters of CZM by method of combining experiment and simulation. The CZM was used for simulation analysis of waste plastic chips, then the delamination influencing rule of the temperature and humidity factors for the plastic chips was summarized. Finally the correctness of delamination simulation results was verified through the WPCB disassembly experiments, then discussed and put forward optimized WPCB disassembly technology for component reuse.

1) Aim at the problem that calculation accuracy of traditional interface crack simulation methods for two-phase material is insufficient, the exponential cohesion theory which best met the Van Der Waals force form was used to analyze the interface crack, and the accuracy of analysis results were improved.

2) In the CZM's analysis, the crack surface measuring experiment and fracture mechanics finite element simulation method were used to get the parameters of old plastic chips' *substrate-molded plastic* interface, the problem of difficultly confirming CZM's parameters was solved.

3) The heating temperature and humidity of old plastic chip had a very large impact on the delamination of internal interface, the higher temperature, the greater amount of moisture absorption , the more prone to occur delamination in the dismantling process.

4) In WPCB's industrial dismantling process, to minimize energy consumption and dismantling costs, we should depend on the environmental temperature and humidity of WPCB to determine whether it is necessary to add the pre-baking process for PCB.

Acknowledgements

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