

AN APPARATUS AND A METHOD FOR CONTROLLING TEMPERATURE OF A HEATING ELEMENT IN A THERMOCOMPRESSION BONDING PROCESS

FIELD OF THE INVENTION

The invention relates to the field of thermocompression bonding of an intermediate film layer to connect different materials. In particular, the invention relates to an apparatus and a method for controlling temperature of a heating element in a thermocompression bonding process for bonding of substrates.

BACKGROUND OF THE INVENTION

Thermocompression bonding machines and processes are commonly used to manufacture consumer electronics including handphones, notebooks, touchpads, electronic gadgets, display modules, touch panels, liquid crystal display (LCD) panels, and the like.

A conventional thermocompression bonding machine has a heating element (often referred to as a thermode) for applying heat and pressure to cure a bond layer intermediate to two substrates so as to bond the substrates to form a substrate assembly. The substrates can include polarizer film materials, film materials, printed circuit board material, glass material or any material that is suitable to meet the requirements in the thermocompression bonding process. Bond layer materials used in the thermocompression bonding can include solder material, anisotropic conductive films (ACF) or any adhesive film layers suitable for interconnection of substrates.

In order to achieve and obtain an optimum bond between the substrates, it is generally recommended that the temperature profile for curing the bond layer (often referred to as "bond line temperature profile") is based on a target bond line temperature profile specified by the bond material supplier. However, this is often difficult to achieve in practice because of heat losses in the thermocompression bonding process. Such heat losses can be due to, for example, the thermal resistance of the bond layer or/and substrates to be bonded and heat losses in parts of the thermocompression bonding machine. As a result of the heat losses during the bonding process, the bond layer may not be cured at the specified bond line temperature profile and this may result in defects such as voids, or insufficient adhesive strength of the bond.

30

Currently, prior to running a new product such as a flex-on-glass substrate assembly which uses a bond layer material having a bond line temperature profile, it is necessary to

determine an input temperature profile for heating a thermode in the thermocompression bonding machine.

To determine the input temperature profile, the user often has to measure the actual temperature in a bond line ("bond line temperature") of a substrate assembly to be bonded.

- 5 In order to compensate for the heat losses explained in the above, the operator has to adjust the input temperature profile to be applied to the thermode. . However, it is difficult to determine by how much an input temperature profile should be adjusted because it depends on the experience of the operator. FIG. 1 illustrates a method 21 for determining the input temperature profile by the operator. Referring to FIG. 1, in a first trial bond for determining
- 10 the thermode temperature, a thermocouple is fixed 22 in the bond line, and the thermode is heated 23 with a input temperature profile based on a specified bond line temperature profile ("target temperature profile") of a bond layer to be used in the production of the substrate assembly . Generally, in the first trial bond, the bond line temperature profile measured 24 in the bond line is lower than a specified bond line temperature profile due to heat losses
- 15 explained in the above. As such, in step 25, if the measured bond line temperature profile is not equal to the target temperature profile, the user has to adjust an input temperature profile in step 26 and apply the adjusted input temperature profile at step 23. To achieve the target bond-line temperature profile, temperature measurements are taken at the bond line and adjustments are made to the input temperature profile until the target temperature profile is
- 20 achieved at the bond line.

Depending on the experience of the operator, an average operator often has to perform a series of trial bonds before a thermode temperature profile for use in production can be determined in step 27.

- 25 However, a disadvantage of the method 21 described in the above is the heavy reliance on user attention and user decisions. User decisions may be influenced by factors such as the user training, experience and product knowledge. Further, the high level of user dependency associated with these methods typically add significant time costs. In high volume production manufacturing environments, time costs significantly impact product yield.

SUMMARY OF THE INVENTION

In accordance with a first aspect of the present invention, there is provided a method of controlling temperature of a heating element in a thermocompression bonding machine to compensate heat loss in a thermocompression bonding process including applying an input temperature profile to the heating element to apply heat to a substrate assembly to be bonded, the method including:

- a) receiving a heating element temperature signal in a controller corresponding to a temperature of the heating element;
 - b) generating a temperature compensation profile in the controller based on the heating element temperature signal and a input temperature signal corresponding to the input temperature profile; and
 - c) controlling power input to the heating element based on the temperature compensation profile;
- wherein the input temperature profile is based on a target temperature profile of a bond line in the substrate assembly.

The step of generating the temperature compensation profile may include:

applying a first series of bond line temperature differential values for a series of time instances in the controller;

calculating a series of heating element temperature differential values from a series of heating element temperature values corresponding to the temperature data of the heating element, and a series of input temperature values corresponding to the input temperature profile at a series of time instances;

deriving a series of temperature compensation values based on the series of heat element temperature differential values and the first series of bond line temperature differential values at a series of time instances.

The step of controlling the power input may include comparing the temperature compensation profile to a pre-determined series of power setting values for applying heat the heating element; generating a temperature compensated power signal based on a power setting value from the pre-determined series of power setting values.

In accordance with a second aspect of the present invention, there is provided a program encoded in a computer-readable recording medium that causes a computer to execute the method.

In accordance with a third aspect of the present invention, there is provided a computer-readable recording medium in which a program causing a computer to execute the method is recorded in a computer-readable form.

The step of applying the first series of bond line temperature differential values may include:

- 5 a) measuring a series of bond line temperature values corresponding to a temperature in a bond line of the substrate assembly for a series of time instances in the thermocompression bonding machine;
- b) calculating a series of bond line temperature differential values from the series of bond line temperature values and the series of input temperature values at a series
10 of time instances to generate a bond line temperature differential profile in a controller of the thermocompression bonding machine;
- c) storing the bond line temperature differential profile in a memory device.

The memory device may be a memory of the controller.

- 15 The method may further include receiving a bond line temperature signal in the controller corresponding to a bond line temperature of the bond line; comparing the bond line temperature signal with the input temperature signal in the controller; compensating the first series of bond line temperature differential values based on a comparison of the bond line temperature signal and the input temperature signal in the controller; and deriving a second series of compensated bond line temperature differential values in the controller.

- 20 The step of compensating the first series of bond line temperature differential values may include applying a multiplier gain to the first series of bond line temperature differential values.

- 25 In accordance with a fourth aspect of the present invention, there is provided a thermocompression bonding machine for compensating heat loss in a thermocompression bonding process including applying an input temperature profile to a heating element to apply heat to a substrate assembly to be bonded, the bonding machine including:

- 30 a first input interface for receiving a heating element temperature profile of the heating element;
- a second input interface for receiving a bond line temperature profile of the substrate assembly to be bonded;

a controller configured to:

- a) receive a heating element temperature signal corresponding to the heating element temperature profile of the heating element;
- b) generate a temperature compensation profile based on the heating element temperature signal and a input temperature signal corresponding to the input temperature profile; and
- c) control power input to the heating element based on the temperature compensation profile.

The memory may be a memory of the controller.

- 10 The bonding machine may further include an input interface adapted to enable the controller to record the temperature differential profile on a recording medium.

The bonding machine may further include a first amplifier connected to a first analog to digital converter for converting one of: the heating element temperature profile and a bond line temperature profile, into a digital signal; and

- 15 a second amplifier connected to a second analog to digital converter for converting one of: the heating element temperature profile and a bond line temperature profile, into a digital signal.

- 20 In accordance with a fifth aspect of the present invention, there is provided an apparatus for controlling temperature of a heating element in a thermocompression bonding machine to compensate heat loss in a thermocompression bonding process including applying an input temperature profile to a thermode to apply heat to a substrate assembly having a bond line, the apparatus having a:

a processor; and

- 25 a memory; the apparatus is configured, under control of the processor, to execute instructions stored in the memory, for a series of time instances:

- a) to receive a heating element temperature signal in a controller corresponding to a temperature of the heating element;
 - b) to generate a temperature compensation profile in the controller based on the heating element temperature signal and a input temperature signal corresponding to the input temperature profile; and
- 30

- c) to control power input to the heating element based on the temperature compensation profile.

The apparatus may be configured to store a series of input temperature values
5 corresponding to the temperature of the heating element at the series of time instances.

The apparatus may be configured to:

- a) receive a first series of bond line temperature differential values for a series of time instances in the controller;
- 10 b) calculate a series of heating element temperature differential values from a series of heating element temperature values corresponding to the temperature data of the heating element, and a series of input temperature values corresponding to the input temperature profile at a series of time instances;
- c) derive a series of temperature compensation values based on the series of heat element temperature differential values and the first series of bond line
15 temperature differential values at a series of time instances.

The apparatus may be configured to:

- a) receive a bond line temperature signal corresponding to a bond line temperature of the bond line;
- b) compare the bond line temperature signal with the input temperature signal;
- 20 c) compensate the first series of bond line temperature differential values based on a comparison of the bond line temperature signal and the input temperature signal; and
- d) derive a second series of compensated bond line temperature differential values.

The apparatus may be configured to apply a multiplier gain to the first series of bond line
25 temperature differential values to obtain the second series of compensated bond line temperature differential values.

The apparatus may be configured to:

- compare the temperature compensation profile to a pre-determined series of power setting values for applying heat the heating element; and .

generate a temperature compensated power signal based on a power setting value from the pre-determined series of power setting values.

5 An advantage of generating the temperature compensation profile in the controller is that temperature control can be synchronized in the thermocompression bonding machine during a thermocompression bonding process.

An advantage of controlling the power input based on the temperature compensation profile is that a method for compensating heat loss can be automated and there is less reliance on an operator's knowledge as to how to adjust the input temperature to be applied to the heating element.

10 Another advantage of controlling the power input is that temperature of the heating element can be controlled and compensated based on the temperature compensated power signal.

BRIEF DESCRIPTION OF DRAWINGS

15 Various embodiments of the invention will now be described, by way of example only, and with reference to the accompanying drawings in which:

FIG. 1 is a flow chart of a known process for determining an input temperature profile to be applied to a heating element in the thermocompression machine;

20 FIG. 2 is a isometric view of a thermocompression bonding machine according to an embodiment;

FIG. 3 is a schematic block diagram of components in the thermocompression bonding machine;

FIG. 4 is a schematic block diagram of a controller of the thermocompression bonding machine;

25 FIG. 5 is a schematic block diagram of a thermocompression bonding machine set-up;

FIG. 6 is a schematic block diagram of a thermocompression bonding machine set-up for a thermocompression bonding process;

FIG. 7 is a flow chart of a method for determining a temperature differential profile;

FIG. 8 is a flow chart of a method of controlling temperature of a heating element to compensate heat loss in a thermocompression bonding process;

FIG. 9 is a flow chart of a method of controlling temperature of a heating element to compensate heat loss in a thermocompression bonding process;

- 5 FIG. 10A is a flow chart of a method of determining a compensated bond line temperature differential profile according to an embodiment;

FIG. 10B is a flow chart of a method of determining a compensated bond line temperature differential profile; and

- 10 FIG. 11 is a flow chart of a method for controlling a power input to the heating element based on a temperature compensation profile.

DETAILED DESCRIPTION

FIG. 2 is an isometric view of a thermocompression bonding machine 30 that can be used in a thermocompression bonding process for manufacturing an item such as for example, touch panel displays, flexible circuit on glass assemblies, or assemblies consisting of different substrate materials. FIG. 2, the thermocompression bonding machine 30 has a thermode assembly 31 before assembly of a heating element 33 (commonly referred to as a thermode) for applying heat for bonding a substrate assembly.. The thermocompression bonding machine 30 has a platform 14 for supporting the substrate assembly during the bonding process. The bonding machine 30 also includes an input unit 32 for receiving an input temperature profile. The input unit 32 may be, for example, a touch panel display or can include a pointing device for receiving input from an operator. The thermocompression bonding machine 30 can have a first input interface for receiving a first temperature input corresponding to a bond line temperature measurement, and a second input interface for receiving a second temperature input corresponding to a thermode temperature measurement. Based on a thermode temperature measurement, the thermocompression bonding machine has a controller 35 that can perform temperature compensation and control a power input to the heating element 33 based on the temperature compensation so as to obtain a target bond line temperature in the bond line of the substrate assembly. Details of the heating element 33 and the controller 35 will be described in FIG. 3 and FIG. 4.

The first and second input interfaces of the thermocompression bonding machine 30 can be or include a socket plug, a temperature reader connector or the like that is configured to enable the controller 35 to receive temperature values measured through a temperature measurement device such as a thermocouple connected to a temperature measurement instrument. In an embodiment, the the thermocompression bonding machine can also be configured to include a third input interface that can detect and receive a program from a storage medium such as a flash memory device, a hard disk drive, an optical disc drive and the like. Still further, the controller 35 can read a program through a data cable that can be connected to an external computer in which the program is executed. The first and second input interfaces can be connectors suitable for receiving thermocouple inputs or the like.

FIG. 3 is a schematic block diagram of components in the thermocompression bonding machine 30 that are related to temperature control of the heating element 33. A controller 35 is configured to receive an input temperature profile 45 from a user or an operator through the input device 32. The controller 35 communicates with a firing unit 34, such as a firing mechanism, by sending a signal 41 to control the operational state of the heating element 33 and/or to control the temperature of the heating element 33. It is appreciated that

a series of drive components, such as for example, a servo motor, can be operatively connected between the controller 35 and the heating element 33 to facilitate moving or positioning of the heating element 33.

Further, the thermocompression bonding machine 30 can include a first amplifier 49 (AMP 49) connected to a first analog to digital converter 50 (ADC 50), and a second amplifier 51 (AMP 51) connected to a second analog to digital converter 52 (ADC 52). The AMP 49 can amplify a first temperature input 43 received through the first input interface and the ADC 50 can convert the amplified temperature input 43 to a digital signal 53 that is passed to the controller 35 via an input 40. For example, if the first temperature input 43 is a series of bond line temperature measurement values at a series of time instances, each of the temperature values can be converted into a signal 53 which can be regarded as a bond line temperature profile. Similarly, a second temperature input 44 can be a series of temperature measurement values measured on the heating element 33 at a series of time instances. The AMP 51 can amplify the second temperature input 44 to obtain an amplified temperature input 44 that is passed to a second analog to digital converter 52 (ADC 52). The second ADC 52 converts the amplified temperature input 44 into a digital signal 54 which can be passed to the controller 35 via an input 39. The digital signal 54 can be regarded as a heating element temperature profile. The controller 35 can be configured to process the digital signals 53 and 54 to control or regulate a power input signal 41 to the firing unit 34. Based on the power input signal 41 from the controller 35, the firing unit 34 applies a firing signal 42 to heat the thermode 33 to obtain the required temperature in the bond line.

Referring to FIG. 4, the controller 35 can include a processor 55 configured to process the signals corresponding to the bond line temperature profile and the heating element temperature profile. The processor 55 can be configured to, for a series of time instances: store a series of input temperature values corresponding to the temperature of the heating element at the series of time instances; store a respective series of sensed temperature value corresponding to the temperature sensed at the bond line at the series of time instances; calculate a series of temperature differential values from the series of input temperature values and the series of sensed temperature values; and derive a compensated temperature profile from the series of temperature differential values.

The controller 35 can have a memory 58 for storing a program which can be run by the controller 35. The processor 55 can also store a signal 56 in the memory 58 or retrieve a signal 57 corresponding to stored data from the memory 58. Alternatively, the controller 35 may have a reader interface circuit (Not shown in FIG. 4) adapted for reading a program from a recording medium such as a flash memory card. As an example, the controller 35

can be a printed circuit board (PCB) assembly. Although in FIG. 4, one signal 41 is sent from the processor 55 for executing a function, it will be appreciated that the processor 55 can send signals according to the desired function to be run by the controller.

FIG. 5 is a schematic block diagram of a thermocompression bonding machine set-up 60 based on the thermocompression machine 30 in FIG. 2. Before production of a substrate assembly in a thermocompression bonding process is started, the set-up 60 is used for determining a bond line temperature differential profile of a substrate assembly 66 to be bonded. The substrate assembly 66 can consist of an intermediate bond layer, a flexible circuit substrate 67 and a glass substrate 68. Alternatively, the substrate assembly 66 can consist of a flexible circuit substrate 67 and a printed circuit board substrate 68. In the set-up 60, the intermediate bond layer is not included. An input temperature profile based on a specified bond line temperature profile ("target temperature profile") of a bond layer can be applied to the heating element 33. The input temperature profile 61 is provided by an operator and can be programmed or stored in a memory of the controller 35.

A thermocouple 64 is fixed in a bond line 65 of a substrate assembly 66 to measure a series of bond line temperature values in the bond line 65 at a series of time instances to obtain a measured bond line temperature profile. The measured bond line temperature profile is amplified and converted into a digital signal by the ADC so as to be received by the controller 35 via the input interface 39. The controller 35 calculates a series of temperature differential values from the input temperature profile 61 and the bond line temperature profile according to the equation (Eq. 1):

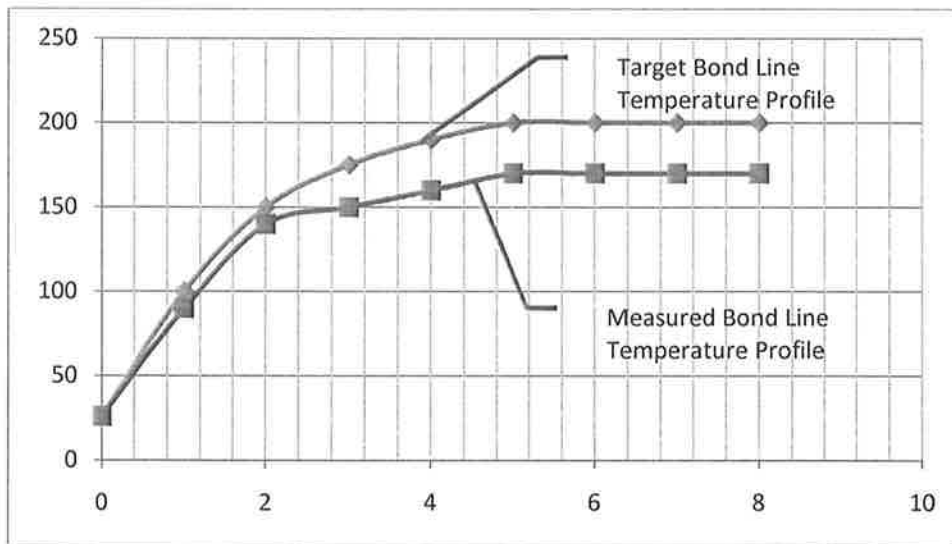
$$D(x) = T_{TBL} - T_{MBL}, \text{-----} \quad (\text{Eq. 1})$$

where $D(x)$ is a temperature differential profile corresponding to a series of temperature differential values at a series of time instances, T_{TBL} is a series of target bond line temperature values at a series of time instances, and T_{MBL} is a series of measured bond line temperature values at a series of time instances. The series of target bond line temperature values can form a target bond line temperature profile and the input temperature profile 61 can be based on the target bond line temperature. The following table, Table 1 illustrates an example of a series of temperature differential values obtained from the set-up 60.

TABLE 1

Time (seconds)	T_{TBL}	T_{MBL}	$D(x)$
0	26	26	0
1	100	90	10
2	150	140	10
3	175	150	25
4	190	160	30
5	200	170	30
6	200	170	30
7	200	170	30
8	200	170	30
.	.	.	.
.	.	.	.
.	.	.	.

The following graph, Graph 1 is an example of a plot of temperature against time based on the values in Table 1 showing the measured bond line temperature and the target bond line temperature at a series of time instances.

Graph 1

The temperature differential profile $D(x)$ can be stored in a memory in the controller 35 or a memory device. It will be appreciated that the $D(x)$ is dependent on the bond layer, and the substrates that form the substrate assembly. Therefore, the equation for $D(x)$ (Eq. 1) can be similarly applied for different substrate materials and different bond layer materials.

By calculating the temperature differential profile based on a substrate assembly to be bonded, it can be regarded that the process of FIG. 7 enables the thermocompression bonding machine 30 to perform automated bond-line compensation based on different substrate assembly configurations and materials quickly. The advantage of measuring the temperature of the bond line temperature in the thermocompression bonding machine is that the temperature measurement process can be synchronized with the thermocompression bonding machine. The advantage of synchronization is that the operator can determine the temperature differential profile $D(x)$ in a single set-up without requiring an external temperature measurement instrument. Further, the bond line temperature differential profile can be stored in a memory device or a memory of the controller 35. In one scenario, an operator can set the number of times required to run a thermocompression bonding set-up process to determine the bond line temperature differential profile of the substrate assembly. For example, the input unit of the thermocompression bonding machine can be configured to allow the operator to enter the number of times to run the thermocompression bonding set-up process.

FIG. 6 is a schematic block diagram of a thermocompression bonding machine set-up 80 for bonding a substrate assembly 70 in a thermocompression bonding process. The substrate assembly 70 consists of an intermediate bond layer 71, a flexible circuit substrate 72 and a glass substrate 73. In the thermocompression bonding process of the substrate assembly 70, a thermocouple 84 is mounted to the heating element or thermode 33 to measure a series of heating element temperature values at a series of time instances which constitute a measured heating element temperature profile. The thermocouple 84 can be located at a centre of the heating element 33 so that the temperature of the heating element can be consistent. The controller 35 can be configured to receive a series of heating element temperature values of the heating element measured for a series of time instances via the second input interface 40. In the controller 35, a temperature compensation profile can be generated based on the heating element temperature profile according to the equation (Eq. 2):

$$A = T_{TBL} - T_{MT} + D(x) \text{ ----- (Eq. 2),}$$

where for a series of time instances, A is a series of temperature compensation values at the series of time instances, T_{TBL} is a series of target bond line temperature values at the series of time instances, and T_{MT} is a series of measured heat element temperature values at the series of time instances. T_{TBL} can be entered by the user as an input temperature profile to the controller. The following table, Table 2 illustrates an example of a series of temperature compensation values obtained relying on the set-up 80 and based on Eq. 2.

Table 2

T_{MT}	T_{TBL}	$D(x)$	A
67.8	67.5	13.4	13.1
70.7	70.3	15.3	14.9
73.4	72.8	16	15.4
75.4	75.5	16.8	16.9
78.3	78	17.6	17.3
80.2	80	18.1	17.9
81.8	82.8	18.7	19.7
84.7	85.3	20	20.6
87.9	88	21	21.1
90.5	90.5	21.8	21.8
91.7	92.5	21.8	22.6
94.4	95.3	23.1	24
97.2	97.8	24.4	25
*	*	*	*
*	*	*	*
*	*	*	*

Based on the temperature compensation profile generated based on Equation 2, the controller 35 can then be configured to controlling a power input to the heating element for compensating the temperature profile of the bond line. In an embodiment, each condition of A is associated with a power input involving a power setting and a duration setting associated with the firing unit. The duration setting can be measured in milliseconds whereas the power setting can be measured in voltage or wattage. Specifically, Table 3 illustrates a look up table consisting of a series of temperature compensation profile conditions corresponding to a power input to the heating element and the duration (time) of the power applied to the heating element. The temperature compensation profile conditions can be derived and stored in the controller.

Table 3

Temperature Compensation Value	Power Input	
A	Power Setting	Duration Setting
<0.1	0	0
<0.5	1	1
<1	2	1
<2	3	1
<4	3	2
<6	3	3
<8	3	4
<10	3	5
<12	3	6
<14	3	7
<16	3	8
<18	3	9
<20	3	10
.	.	.
.	.	.
.	.	.

By comparing the value of the temperature compensation profile A to a series of power inputs listed in table 3, the controller 35 can control a power input to the heating element to increase or ramp the temperature of the heating element according to the Power and the duration. The higher the power and the duration will mean that the ramping of temperature of the heating element will be higher. It will be appreciated that the quality of a bond can also depend on the coefficient of thermal expansion of the materials. In one scenario, after the equation 2 is applied to derive the temperature compensation value and a power input based on the temperature compensation value is applied, the measured bond line temperature can be equal to the target bond line temperature, i.e, a condition that is as follows.

$$T_{MBL} = T_{TBL} \text{ ----- (Condition 1)}$$

However, for heat transfer in transient system such as in a thermocompression bonding process where the boundary conditions can vary, the heat loss in the thermocompression bonding process is not linear. For example, when the heating element is at higher temperatures, there is more heat loss such that it results in the measured bond line temperature being less than the target bond line temperature as described in the following condition:

$$T_{MBL} < T_{TBL} \text{ ----- (Condition 2)}$$

- 10 In the event where the above condition 2 exists, a function can be implemented to compensate for losses at higher temperatures. In an embodiment, $D(x)$ can be modified to obtain a compensated $D'(x)$ by applying a multiplier gain G to $D(x)$ [i.e. in this case $D'(x) = G \cdot D(x)$] to compensate for heat loss according to the equation (Eq. 3),

$$15 \quad A' = T_{TBL} - T_{MT} + G \cdot D(x) \text{ ----- (Eq. 3),}$$

where A' is a temperature compensation profile, and G is a multiplier gain.

G can be obtained based on iteration, i.e. conducting trial bond tests on a thermocompression bonding machine. For optimizing a bond line temperature in the thermocompression bonding process, a preferred condition is as follows:

$$20 \quad G = 1.2 \text{ ----- (Condition 3)}$$

Still further, in an embodiment, $D(x)$ can be modified to obtain a compensated $D'(x)$ by adjusting T_{TBL} and repeating a process of determining the bond line temperature differential profile based on the step up 60 in FIG. 5.

- FIG. 7 is a flow chart of a method 90 for determining a temperature differential profile for compensating heat loss performed by the controller 35 of FIG. 4C. A flow for determining the temperature differential profile will be described with reference to the thermocompression bonding machine set-up of FIG. 5. When a target temperature profile is applied to the heating element 33 in step 91, the temperature of the bond line temperature can be measured in step 92 and recorded in a memory of the controller 35. In step 93, a temperature differential profile can be calculated by the controller 35 based on the target temperature profile and the measured bond line temperature profile. In step 94, the
- 25
- 30

temperature differential profile can be stored in a memory device. The memory device can be a memory in the controller 35 or a recordable medium such as a flash memory card.

FIG. 8 is a flow chart of a method 100 for compensating heat loss in a thermocompression bonding process. In step 101, a target temperature profile is applied to the heating element 33. In step 102, the temperature of the heating element 33 can be measured and recorded in the memory of the controller 35. In step 103, a temperature compensation profile A can be calculated using equation 2 described in the above and the temperature compensation profile A can be used by the controller 35 to control a power input to the heating element 33 for compensating heat loss in step 104. In a scenario, a bond line temperature of the substrate assembly can be measured to determine if the bond line temperature is equal to the target bond line temperature required to achieve optimum bond quality in the substrate assembly.

FIG. 9 is a flow chart of another method 200 for compensating heat loss in a thermocompression bonding process. Steps 201, 202, 203 in method 200 of FIG. 9 are similar in operation to the steps 101, 102 and 103 in method 100 of FIG. 8. In step 204, the controller controls a power input to the heating element 33 based on the temperature compensation value in step 203, and a bond line temperature is measured in step 205. In step 206, the measured bond line temperature is checked if condition 1, i.e. $T_{MBL} = T_{TBL}$ is met. If condition 1 is not met corresponding to a NO condition, i.e. $T_{MBL} < T_{TBL}$, a compensated bond line temperature differential profile $D'(x)$ is calculated in step 208 and steps 201 and 202 are repeated to obtain a second compensation value A' in step 203. The temperature compensation value A' is calculated in step 208 according to the equation:

$$A' = T_{TBL} - T_{MT} + D(x),$$

where $D(x) = D'(x)$ which corresponds to a compensated bond line temperature differential profile obtained according to the method 90 in FIG. 7. In a first production run, a value of G is set to 1. However, depending on the measured bond line temperature, the value of G can be adjusted to 1.2. Based on the temperature compensation value A' , a power input to the heating element can be controlled and the process ends when the condition $T_{MBL} = T_{TBL}$ is met, i.e. corresponding to a YES condition in 209.

FIG. 10A is a flow chart showing a further method 210 of determining a compensated bond line temperature differential profile $D'(x)$. In step 211, a second input temperature profile $T'(x)$ is applied to the heating element. $T'(x)$ is calculated according to the equation:

$$T'(x) = T_{TBL} + D(x),$$

5 where $D(x)$ corresponds to the temperature differential profile obtained according to the method 90 in FIG. 7. Similar to step 92 of method 90, in step 212, a bond line temperature T'_{MBL} is measured and recorded in a memory of the controller 35. In step 213, a compensated temperature differential profile $D'(x)$ can be calculated by the controller 35 based on the second input temperature profile and the measured bond line temperature
10 profile. In a scenario, the method 210 can be used in applications where the substrate assemblies to be bonded consist of a flexible circuit substrate and a printed circuit boards having conductive metal circuit patterns such as for example, copper circuit patterns.

FIG. 10B is a flow chart showing another method 215 of determining a compensated bond line temperature differential profile $D'(x)$. Similar to step 91 of method 90 in FIG. 7, a target
15 temperature profile T_{TBL} can be applied to the thermode. Similar to step 92 of method 90, in step 217, a bond line temperature T_{MBL} is measured and recorded in a memory of the controller 35. In step 218, a compensated temperature differential profile $D'(x)$ can be calculated by the controller 35 according to the equation:

$$D'(x) = G * (T_{TBL} - T_{MBL}),$$

20 where G is a multiplier gain derived based on the thermocompression machine. In a first production run, a value of G is set to 1. However, depending on the measured bond line temperature, a value of G can be adjusted to 1.2. Based on the temperature compensation value A' , a power input to the heating element can be controlled and the process ends when the condition $T_{MBL} = T_{TBL}$ is met, i.e. corresponding to a YES condition in 209. In one
25 scenario, the method 215 can be used in applications where the substrate assemblies to be bonded consist of a flexible circuit substrate and a glass substrate.

FIG. 11 is a flow chart showing a process 400 for controlling a power input to the heating element based on the temperature compensation value A or A' in Step 104 of FIG. 8 and FIG. 9. When controlling of a power input to the heating element 33 is started in step 401,
30 the temperature compensation value A or A' is compared in step 402 to a series of pre-determined power input settings corresponding to a series of conditions for A or A' . For example, the power input settings can include a power setting (measured in voltage) and a duration setting of a firing circuit in the firing unit 34, and a condition of A or A' can be

associated with a pre-determined power setting. For example, referring to Table 3, if the value of A or A' is less than 0.1, the power setting is 1 and the duration setting is 1, hence a set of pre-determined power input settings is selected based on a condition of A in step 403. The duration setting can be a time setting measured in milliseconds. Accordingly, power is applied to the thermode 33 to apply heat to the substrate assembly based on the selected power input setting in step 404.

An advantage of the above described temperature compensation method is that a one-time setup can be performed for thermocompression bonding of each type of product based on the same substrate assembly. It will be appreciated that to heat the heating element to the required temperature to compensate for heat loss in the bond line, the firing unit or the firing circuit can be configured accordingly. For example, the number of points in a temperature profile can vary, such as the temperature is near the set temperature, the duration of the firing will be smaller. When the duration is smaller, the frequency of firing might be more. As such, the number of points varies in the entire temperature profile. It will be appreciated that the above described method can be used in standard firing units known to a skilled person in the field of thermocompression bonding. For example, the firing unit can include a high current or high voltage device operatively coupled to a firing relay circuit for controlling a high current device from the controller. The firing relay circuit can include a device for switching the high current device such as for example, a power relay switch, a semiconductor switch or the like. The high current device may be a heater cartridge of different watt (power size) or transformer (of different rating) that can be used to get the bond line temperature to the target bond line temperature based on the temperature compensation profile. The temperature compensation cycle for each new substrate assembly can be optimized quickly.

The advantage of the above described methods according to the embodiments is that the temperature compensation for the bonding process is less dependent on the skill of the operator because the operator does not need to adjust an input temperature so as to compensate heat loss in the bond line of the substrate assembly in the thermocompression bonding process.

While embodiments of the invention have been particularly shown and described with reference to specific embodiments, it should be understood by those skilled in the art that various changes in form and detail may be made therein without departing from the spirit and scope of the invention as defined by the appended claims. The scope of the invention is thus indicated by the appended claims and all changes which come within the meaning and range of equivalency of the claims are therefore intended to be embraced.

CLAIMS

1. A method of controlling temperature of a heating element in a thermocompression bonding machine to compensate heat loss in a thermocompression bonding process including applying an input temperature profile to the heating element to apply heat to a substrate assembly to be bonded, the method including:
 - a) receiving a heating element temperature signal in a controller corresponding to a temperature of the heating element;
 - b) generating a temperature compensation profile in the controller based on the heating element temperature signal and a input temperature signal corresponding to the input temperature profile; and
 - c) controlling power input to the heating element based on the temperature compensation profile;
 wherein the input temperature profile is based on a target temperature profile of a bond line in the substrate assembly.
2. The method according to claim 1, wherein generating the temperature compensation profile includes:
 - applying a first series of bond line temperature differential values for a series of time instances in the controller;
 - calculating a series of heating element temperature differential values from a series of heating element temperature values corresponding to the temperature data of the heating element, and a series of input temperature values corresponding to the input temperature profile at a series of time instances;
 - deriving a series of temperature compensation values based on the series of heat element temperature differential values and the first series of bond line temperature differential values at a series of time instances.
3. The method according to claim 1 or 2, wherein controlling the power input includes:
 - comparing the temperature compensation profile to a pre-determined series of power setting values for applying heat the heating element;
 - generating a temperature compensated power signal based on a power setting value from the pre-determined series of power setting values.
4. A program encoded in a computer-readable recording medium that causes a computer to execute the method according to any one of claims 1 to 4.

5. A computer-readable recording medium in which a program causing a computer to execute the method according to any one of claims 1 to 4 is recorded in a computer-readable form.

6. The method according to claim 2, wherein applying the first series of bond line temperature differential values includes:

- a) measuring a series of bond line temperature values corresponding to a temperature in a bond line of the substrate assembly for a series of time instances in the thermocompression bonding machine;
- b) calculating a series of bond line temperature differential values from the series of bond line temperature values and the series of input temperature values at a series of time instances to generate a bond line temperature differential profile in a controller of the thermocompression bonding machine;
- c) storing the bond line temperature differential profile in a memory device.

7. The method according to any one of the preceding claims, wherein the memory device is a memory of the controller.

8. The method according to any one of the preceding claims, the method further including:

receiving a bond line temperature signal in the controller corresponding to a bond line temperature of the bond line;

comparing the bond line temperature signal with the input temperature signal in the controller;

compensating the first series of bond line temperature differential values based on a comparison of the bond line temperature signal and the input temperature signal in the controller; and

deriving a second series of compensated bond line temperature differential values in the controller.

9. The method according to any one of the preceding claims wherein compensating the first series of bond line temperature differential values includes:

applying a multiplier gain to the first series of bond line temperature differential values.

10. A thermocompression bonding process for bonding a glass substrate to a flexible circuit substrate comprising the steps according to the method according to any one of the preceding claims.

11. A thermocompression bonding machine for compensating heat loss in a thermocompression bonding process including applying an input temperature profile to a heating element to apply heat to a substrate assembly to be bonded, the bonding machine including:

a first input interface for receiving a heating element temperature profile of the heating element;

a second input interface for receiving a bond line temperature profile of the substrate assembly to be bonded;

a controller configured to:

d) receive a heating element temperature signal corresponding to the heating element temperature profile of the heating element;

e) generate a temperature compensation profile based on the heating element temperature signal and a input temperature signal corresponding to the input temperature profile; and

f) control power input to the heating element based on the temperature compensation profile.

12. The bonding machine according to claim 11, further comprising: a first amplifier connected to a first analog to digital converter for converting one of: the heating element temperature profile and a bond line temperature profile, into a digital signal; and

a second amplifier connected to a second analog to digital converter for converting one of: the heating element temperature profile and a bond line temperature profile, into a digital signal.

13. The bonding machine according to any one of claims 11 to 12, wherein the controller is configured to:

calculate a series of temperature differential values based on the input temperature profile and one of: the bond line temperature profile and the heating element temperature profile to obtain a temperature differential profile;

calculate a temperature compensation profile based on the series of temperature differential values; and

control a power input to the heating element based on the temperature compensation profile.

14. The bonding machine according to any one of claims 11 to 13, wherein the controller has a memory for storing one of: the input temperature profile, the heating element temperature profile or the bond line temperature profile.

15. The bonding machine according to claim 13, further comprising an input interface adapted to enable the controller to record the temperature differential profile on a recording medium.

16. An apparatus for controlling temperature of a heating element in a thermocompression bonding machine to compensate heat loss in a thermocompression bonding process including applying an input temperature profile to a thermode to apply heat to a substrate assembly having a bond line, the apparatus having a:

a processor; and

a memory; the apparatus is configured, under control of the processor, to execute instructions stored in the memory, for a series of time instances:

d) to receive a heating element temperature signal in a controller corresponding to a temperature of the heating element;

e) to generate a temperature compensation profile in the controller based on the heating element temperature signal and a input temperature signal corresponding to the input temperature profile; and

f) to control power input to the heating element based on the temperature compensation profile.

17. The apparatus according to claim 16, wherein the apparatus is configured to store a series of input temperature values corresponding to the temperature of the heating element at the series of time instances.

18. The apparatus according to claim 16 or claim 17, wherein the apparatus is configured to:

a) receive a first series of bond line temperature differential values for a series of time instances in the controller;

b) calculate a series of heating element temperature differential values from a series of heating element temperature values corresponding to the temperature data of the heating element, and a series of input temperature values corresponding to the input temperature profile at a series of time instances;

c) derive a series of temperature compensation values based on the series of heat element temperature differential values and the first series of bond line temperature differential values at a series of time instances.

19. The apparatus according to claim 18, wherein the apparatus is configured to:

a) receive a bond line temperature signal corresponding to a bond line temperature of the bond line;

b) compare the bond line temperature signal with the input temperature signal;

c) compensate the first series of bond line temperature differential values based on a comparison of the bond line temperature signal and the input temperature signal; and

d) derive a second series of compensated bond line temperature differential values.

20. The apparatus according to claim 19 wherein the apparatus is configured to apply a multiplier gain to the first series of bond line temperature differential values to obtain the second series of compensated bond line temperature differential values.

21. The apparatus according to any one of claims 16 to 20, wherein the apparatus is configured to:

compare the temperature compensation profile to a pre-determined series of power setting values for applying heat the heating element; and

generate a temperature compensated power signal based on a power setting value from the pre-determined series of power setting values.