Task Scheduling Control of BGA Solder Joint Process in Flexible Manufacturing System

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Abstract – *This paper describes an open loop control method of the solder joint process in a rework station for faulty Printed Circuit Board (PCBs) containing electronic components in packages Ball Grid Arrays (BGAs). In particular, a mathematical model describing the solder joint process is, first of all, obtained. Then, the desired thermal profile of the junctions BGA-PCB is determined according to the physical constraints of the rework station framework. The control parameters corresponding to the above desired thermal profile are identified using the above mathematical model. Finally, the open loop control algorithm is implemented on the supervisor interface of the rework station in order to carried out experimental validation of the proposed method.*

1. Introduction

In the flexible manufacturing system (FMS) of electronic devices, the increasing request of integration of more and more functions in a single die, in order to obtain small components with low working currents, has as a result the gradual disuses of Pin Through Hole (PTH) insertion technology of the electronic components to advantage of Surface Mounted Technology (SMT) [1].

As is well know, the SMT technology is divided in two subfamilies. The first consists of components whose terminations fall in the boundary of the packages and is known as Fine Pitch Technology (FPT) and Ultra Fine Pitch Technology (UFPT). It is characterized by a lead pitch upper to 450 micron and a high pin count. The second is called Area Array (AA) and consists of BGA (Ball Grid Array) packages [2].

The principal characteristic of the BGA package [3] is the connection placed on the bottom side of the component exploiting the whole area under it. In this way it is possible to increase the number of I/O terminations (actually upper 5000), without reduction of the lead pitch. This allows to increase the upper cut-off frequency of the component due to the reduction of the parasite capacities and inductances.

However, the BGA packages present inspection and assembly problems specially in the rework process [2], [4]. Actually the closed loop control of the thermal profile of the welding process of the component on the PCB is not reproducible, as in the reflow oven, because the balls are not directly accessible for measurement. In order to give the correct quantity of heat to all the welding joints, dedicated rework stations are used which simulate the thermal environment inside the reflow oven in the principal production chain [2].

The control parameters used to plan the task scheduling actions of the rework station are obtained off line during the setup operation, and then stored in the supervisor interface to be used during the rework cycle. These parameters can be obtained either by trial and errors or direct methods. In the trials and errors methods, the parameters are identified after a lot of test cycles executed on the PCB. Starting from a set of acceptable initial values, the control parameters are adjusted according to some empiric rules so as to reduce the mismatch of the actual thermal profile corresponding to the actual values of the parameters themselves and the desired thermal profile. This method requires a very long

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setup time, expert operators and a good knowledge of the influence of the control parameters on the behavior of the machine.

In the direct methods, it is possible to monitor the shape of the thermal profile during the solder joint process by means of thermocouples touching the balls which allow to measure the interval of time elapsing between two successive events that define the solder thermal profile itself. However, the control parameters are obtained by trial and errors.

In the present paper it is illustrated a systematic method for the off-line identification of the control parameters of the solder joint process of BGAs on PCBs in the rework station, based on a suitable mathematical model of the solder process itself. This method consists of the following phases: a) determination of a mathematical model to approximate the heating process; b) off-line determination of the control parameters sequence that determines a suitable thermal profile using the above mathematical model. The aim of the method is the reduction of the setup time of rework station together with increasing of its performances.

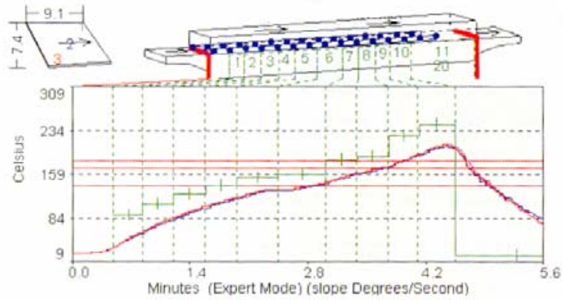
The approach has been used for a rework station DRS-24. The experimental results obtained allow to prove the validity of proposed method. In fact, the above machine has been inserted in the production line of the factory.

2. Rework work-cell for BGA placement

The BGAs are placed on the PCB after the solder serigraphy sub process through the production line dedicated to the SMT technology. The solder thermal profile is obtained in the reflow oven through the regulation of both the temperature of 10 emitters heat panels and the speed of the conveyer, as shown in Fig.1. The temperature on the cross over sections of the PCB surface is approximately homogeneous. This implies that all the components placed on the top surface of the board are subject to the same well defined thermal profile, whereas the components on the bottom side are soldered successively in a wave oven. At the end of the assembly line the final test, named In Circuit Test (ICT), is activated and the faulty boards are removed from the assembly line to be reworked.

The rework process consists in removing and re-assembling the faulty component from a PCB populated by other components. The rework machines are '*general purpose*', i.e. they can be used for reprocessing a wide class of components like UFPTs and BGAs, as long as the control parameters that produce the desired solder joint thermal profile are identified.

The rework process consists of two phases. In the first phase, a set of events are scheduled for positioning the component on the PCB. In the second phase, a set of '*time driven'* events are scheduled by a supervision control system to activate the solder joint process.



	Peak	Max Rising Slope	Time Between 140/170	Total Time Above 183
1 LEFT CORNER	210.0	1.63	52.00	46.25
2 CENTER	208.1	1.38	51.60	43.99
3 RIGHT CORNER	210.3	1.57	51.62	45.93

Figure 1. Reflow oven and solder thermal profile.

The positioning of the component on the PCB is carried out by a mechanical system consisting of a prism lens which captures the images of both the pattern platforms and the bottom side of the BGA component and convey them to an optic microscope. Successively, a nozzle is lowered on the component and the solder process starts. During the positioning process, transition events $(e_1,t_1,)$, $(e_2,t_2,)$,…, (e_n,t_n), are driven by a footswitch sensor characterized by some quantities that activate or deactivate the positioning process itself.

In the second phase, time driven events are scheduled by the quantities: nitrogen flow temperature of the upper solder head (*nozzle*), air flow temperature of the lower diffuser and duration allowed to each event. A decentralized control system allows the set-points of the above quantities to remain constant during the scheduling of all the events. In the Fig. 2 it is shown the control system block diagram.

A numerical control system is used for controlling the instantaneous values of the temperature and flow of the nitrogen in the nozzle and the positioning of the BGA carried out by a servomotor; it gives also the set-points to two decentralized PID control systems of the temperature of the air flows of the left and right diffusers.

3. Description of the BGA solder joint process

Now, the problem to be addressed is the determination of parameters that produce the event scheduling in the BGA solder joint process.

Let us consider, first of all, that the generic BGA component consists of a die connected through wirebond to some channels that end in the balls in the bottom side of the component.

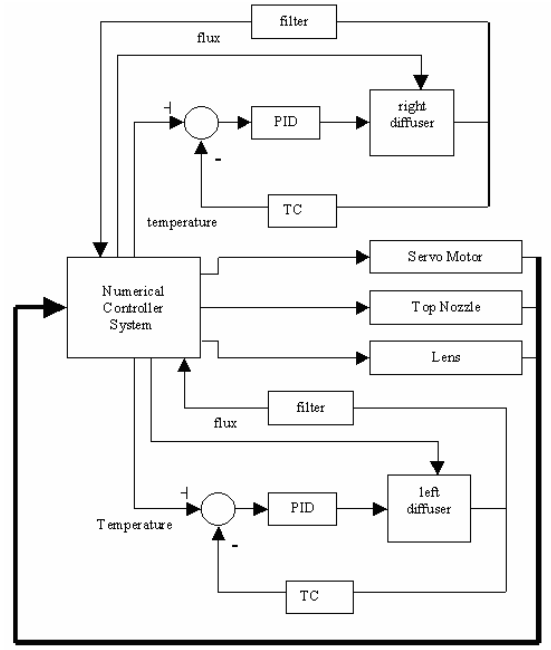


Figure 2 Control system of the rework station

A numerical control system is used for controlling the instantaneous values of the temperature and flow of the nitrogen in the nozzle and the positioning of the BGA carried out by a servomotor; it gives also the set-points to two decentralized PID control systems of the temperature of the air flows of the left and right diffusers.

The balls are composed by 90St/10Pb eutectic league that melts according to a well determined thermal profile [5]. In the re-flow process, constraints on the slope of the time temperature profile and the maximum permanence time above the fusion temperature (183 °C) have to be satisfied in order to avoid, respectively, the stress of both the component and the PCB and the ‘popcorn effect’ on the BGA substrate [6].

The desired thermal profile is shown in Fig. 3 [7]. The solder joint profile is obtained by the control of the following parameters: top and bottom temperatures, T_b and T_t, top and bottom flows, F_b and F_t, and event duration Δt. These parameters are necessary to reproduce inside the nozzle a thermal environment like to that inside the re-flow oven.

By varying these quantities in the five dimensional space $(T_b, T_t, F_b, F_t, \Delta t)$, a thermal profile family is obtained from which it is necessary to extract the thermal profile which matches the profile shown in Fig. 3 minimizing a given performance index.

The ball temperature to be controlled is not directly measurable because of the component structure. This implies that a closed loop control of a time-temperature profile cannot be effected; instead, it is effected an open loop control based on the scheduling of a sequence of events controlled by the duration of each event, whereas each event evolves at given values of the parameters which characterizes it.

To obtain the values of the time duration and the parameters of each event the following procedure is used. The ball temperature is measured connecting thermocouples to the balls themselves under the bottom side of the component as shown in Fig. 4; obviously, this operation is destructive. In this way, it is possible to identify an input-output mathematical model which allows us to determine the values of the parameters of the events that determine the suitable thermal profile. The parameters that characterize each event are stored in the supervision program which is used for all the components with the same characteristics.

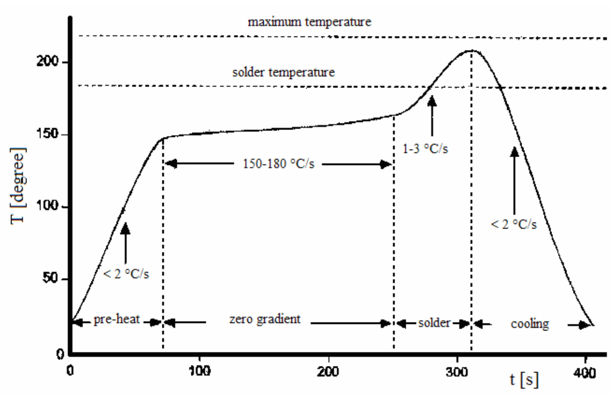


Figure 3 Thermal profile

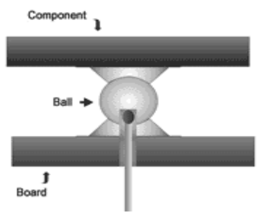


Figure 4 Thermocouples positioning

The desired thermal profile can be divided in four regions that are characterized by different slopes. Assuming that the initial state of the controlled variable is equal to the value of the environment temperature, 26 °C, the first event is characterized by the transition of the temperature from 26 to 150 °C with maximum slope equal to 2 °C/s. The second event is characterized by the transition of the temperature from 150 °C to 180 °C with a slope in the range of [0.16-0.2] °C/s. The third event is characterized by the transition of the temperature from 180 to 210 °C with a slope up to 3 °C/s, while the fourth event is characterized by the transition of the temperature from 210 to 130 °C with a slope of -2 °C/s. Finally, a transition of the temperature from 130 °C to the environment temperature occurs without any control.

Some simplifications are now introduced which allow to deal with the rework process considering a SISO system. First of all, it is experimentally observed that temperature and air flow at the bottom only allow to polarize the PCB temperature around 90 °C, whereas the temperature and the nitrogen flow at the top determine the profile dynamics. This suggests to assume constant the above quantities at the bottom to reduce the number of the parameters to be determined .

It is experimentally observed that continuous variations of the nitrogen flux at the top, F_t, is not convenient in order to determine the desired thermal profile, which suggests to discretize the range of variation of the flux. In this paper four values of the flux are considered: 25 %, 50 %, 75 % and 100 % of its maximum value.

The approach used for the identification of the parameters is shown in Fig. 5. Through the Simulation subsystem it is regulated the variable y that represents the theoretical thermal profile of the balls while u is the desired thermal profile.

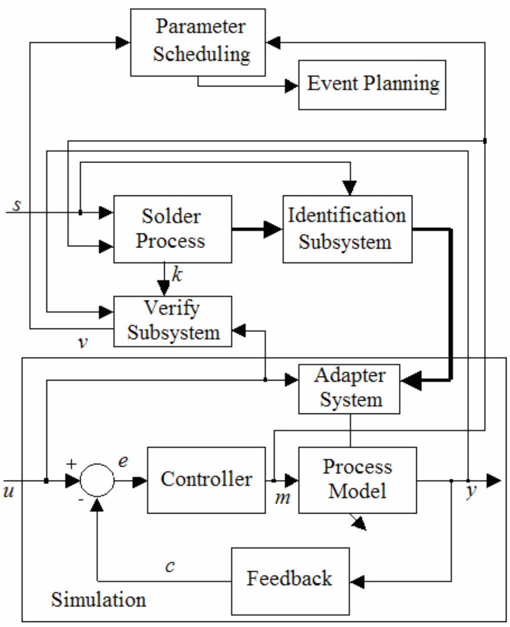


Figure 5 Control system block diagram

The admissible impulse responses obtained by the Identification subsystem is transmitted to Simulation subsystem. Every impulsive response of the system is parameterized by constant flux and is transmitted to the Adapter System in every control region.

The control variable m (top temperature) is transmitted to the parameter scheduling block. It acts on the physical process, which returns the balls thermal profile value k by the excitement signal s. The physical output quantity k, is compared with output quantity y and the desired signal u of the Simulation subsystem in the Verify subsystem, with the aim to value if the approximations performed in the subsystem Simulations are contained within a band of tolerance.

The identification of the impulsive response is obtained in the Identification subsystem. Every impulsive response is determined beginning from the sequence of I/O data obtained by an data acquisition instrument called superMOLE.

If the approximations are valid, the output of the Verify Subsystem activates the control parameter determination process, beginning from the sequence of the control variable m; otherwise, it is necessary to choose new regions for the event transition on the basis of the error given by the Verify Subsystem.

4. Identification of the impulsive response

The mathematical model of the system shown in Fig. 6, is characterized by a family of impulsive responses parameterized with constant top nitrogen flow. It has been experimentally seen that these responses are overdamped. So, the expression of the step response, physically a temperature, at a given value of F_t, can be assumed as follows:

$$w_{-1}(t,F_t) = y_{di}(t) + y_{1i}(t) + y_{2i}(t)\,, \tag{1}$$

where:

$$y_{di}(t) = y_{ri}(1 - e^{-\frac{t}{\tau_{di}}})\,, \tag{2}$$

$$y_{1i}(t) = \alpha_i e^{-\frac{t}{\tau_{1i}}}\,, \tag{3}$$

$$y_{2i}(t) = \beta_i e^{-\frac{t}{\tau_{2i}}}\,. \tag{4}$$

To compute the parameters appearing in (2)-(4) the follow procedure is used.

1. Through the SuperMole, n_s samples of the step response $w_{-1}^s(kT_s)$ are acquired at a given sampling period T_s. It is convenient to acquire two temperature sequences measured in the central part and in the peripheral part of the BGA, and to get a sequence computed as mean of the two sequences.
2. y_{ri} and τ_{di} are determined from the sequence obtained at the step 1, as follows:

$$y_{ri} = \lim_{k\to\infty} w_{-1}^s(kT_s, F_t)\,, \tag{5}$$

$$\tau_{di} = -\frac{1}{NT_s}\sum_{k=0}^{N-1}\frac{1}{k}\ln\left(\frac{y_{ri} - w_{-1}^s(kT_s, F_t)}{y_{ri}}\right), \tag{6}$$

approximating the step response with the term $y_{di}(t)$.

3. The parameters of the two modes y_{1i} and y_{2i} are determined so as to minimize the index:

$$J = \sum_{k=0}^{N-1} [w^{s}_{-1}(kT_s, F_t) - w_{-1}(kT_s, F_t)]^2 \cdot \tag{7}$$

4. Finally, the impulsive response $w(kT_s, F_t)$ is computed as derivative of the step response.

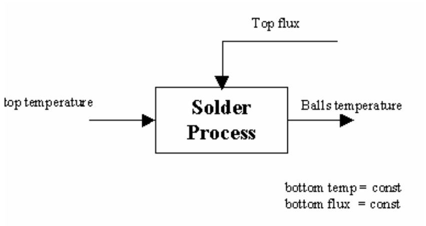


Figure 6 Simplified system I/O

5. Identification of parameter sequence

5.1 Formulation of the parameter identification problem

The formulation of the control parameter identification problem for the event scheduling of the solder joint process is described as follows. Let us refer to the mathematical model given by the impulsive response $w(kT_s, F_t)$, where F_t assumes the four constant values already specified. The problem is the identification of the events, $\{(e_i, t_i)\}$, where t_i is the duration of the event i and e_i is a member of the set $\{(F_b, T_b, F_t, T_t)\}$ assuming flux and temperature of the bottom, F_b and T_b, constant during the rework process, subject to the following constraints:

- maximum temperature, T_{px};
- maximum value of the top temperature, T_{tx};
- maximum value of the bottom temperature, T_{bx};
- top flow $F_t \in \{0.25\, F_{tx}, 0.5\, F_{tx}, 0.75\, F_{tx}, F_{tx}\}$;
- constant bottom flow;
- maximum number of events, N_x;
- quantity of heat for solder joint, Q_r.

5.2 Determination of the parameter sequence

Now, let us consider the problem of the determination of the parameter sequence for the event scheduling. The parameters which must be determined are T_t, F_t and t_i.

To determine the parameter sequence, observe that the impulse response w of the process can be written as follows:

$$w = x_1 w_1 + x_2 w_2 + x_3 w_3 + x_4 w_4, \tag{8}$$

where x_i is a binary variable depending on the control region which satisfies the constraint:

$$x_i = \{0,1\}, \quad \sum_{i=1}^{4} x_i > 0 . \tag{9}$$

Putting:

$$\boldsymbol{x} = [x_1 \quad x_2 \quad x_3 \quad x_4]^T, \tag{10}$$

$$\tilde{\mathbf{w}} = [\mathrm{w}_1 \quad \mathrm{w}_2 \quad \mathrm{w}_3 \quad \mathrm{w}_4]^{\mathrm{T}}, \tag{11}$$

the impulse response can be written as it follows:

$$w = \boldsymbol{x}^{\mathrm{T}} \tilde{\boldsymbol{w}} . \tag{12}$$

The vector **x** can be chosen in the four control regions as follows.

1. The environment temperature is assumed as initial state related to the region 1.
2. For each of the admissible configurations of the vector $\boldsymbol{x}$, the thermal profile produced by the Simulation system is stored. Then, the vector $\boldsymbol{x}$ is chosen so as to minimize the average quadratic error obtained as difference of the thermal profile relative to the region 1 and the piece of the reference thermal profile relative to the same region 1.
3. The final state of the region 1 is assumed as initial state for the region 2 and the algorithm proceeds as indicated at the step 2, up to complete the four regions.

The sequence of the **x** vector determines the whole impulse response.

Note that the actual temperature of the top reaches the desired value after a transient of finite duration. To take into account this phenomenon, a new block has been inserted between the controller of the Simulation system (cf. Fig. 5) and the model of the process. This block has m as input, m' as output and w_r as impulse response. This response is that of a first order system whose time constant is obtained empirically.

After having identified the mathematical model of the process, it is possible to find the actual controlled variable through the following recursive algorithm:

$$m_i^{'}(k)=\frac{u(k)-\sum_{j=1}^{N-1}\left[m_i(k-j)w_i(j)+m_i^{'}(k-j)w_r(j)w_i(0)\right]}{w_i(0)w_r(0)}, \tag{13}$$

with:

$$m_i^{'}(k)=0\,,\quad m_i(k)=0\quad \text{for } k<0\,, \tag{14}$$

$$m_i^{'}(0)=\frac{u(0)}{w_i(0)w_r(0)}, \tag{15}$$

$$m_i(k)=m_i^{'}(k)\cdot w_r(0)+\sum_{j=1}^{N-1}m_i^{'}(k-j)\cdot w_r(j), \tag{16}$$

$$M_{i\min}^{'}(k)\le m_i^{'}(k)\le M_{i\max}(k). \tag{17}$$

The parameter sequence of F_t is obtained by the one-to-one correspondence between the binary vector **x** and the flux vector **f** defined, in percent, as follows:

$$\boldsymbol{f}=[25\ 50\ 75\ 100]^T\,. \tag{18}$$

6. Experimental implementation and validation of the proposed method

The proposed method has been implemented and tested in a manufacturing work-cell which employs an Zevac DRS-24 Rework station.

The data necessary to calculate the impulsive response of the solder process are obtained from the samples of the step response of the system described in the Section 4. The final shapes of the experimental step response and the corresponding impulse response obtained by the procedure described in the Section 4, are shown in Figs. 7 and 8.

The shape of the thermal profile, given by the Simulation system is shown in Fig.9, where the curve 1 represents the shape of the controlled variable (top temperature), while curves 3 and 4 represent, respectively, the shapes of the thermal profile at the corner and at the center of the BGA component.

In Table 1 the values of the control parameters for the task scheduling planning of the whole control system are reassumed.

The experimental thermal profile at the center and at the corner of the component, after the storage of the parameters on the rework machine memory, are shown in Fig.10. In Figs. 11-12 are, also shown the absolute error given by the difference between the theoretical thermal profile and the relative experimental value. We can see that in both cases the absolute error is under the band of tolerance (10 °C), except for the initial error peak caused by the difference between the environment temperature and the temperature of the PCB.

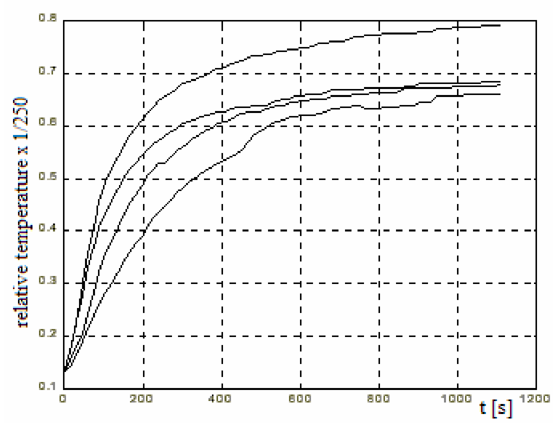


Figure 7 Experimentally step response

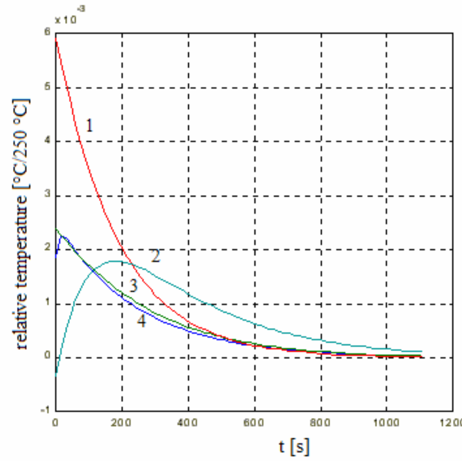


Figure 8 Theoretical impulsive response

Table 1 List of the events

TEMP TOP UNIT	FLUX %	TEMP BOTTOM UNIT	FLUX BOTTOM %	TIME (S)
148	50	320	High	120
322	50	320	High	240
363	75	320	High	75
398	75	320	High	30
180	50	320	Low	120
18	80	26	Zero	100

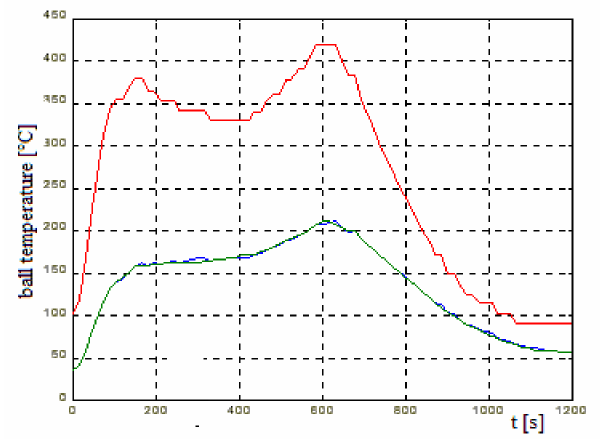


Figure 9 Mathematical thermal profile

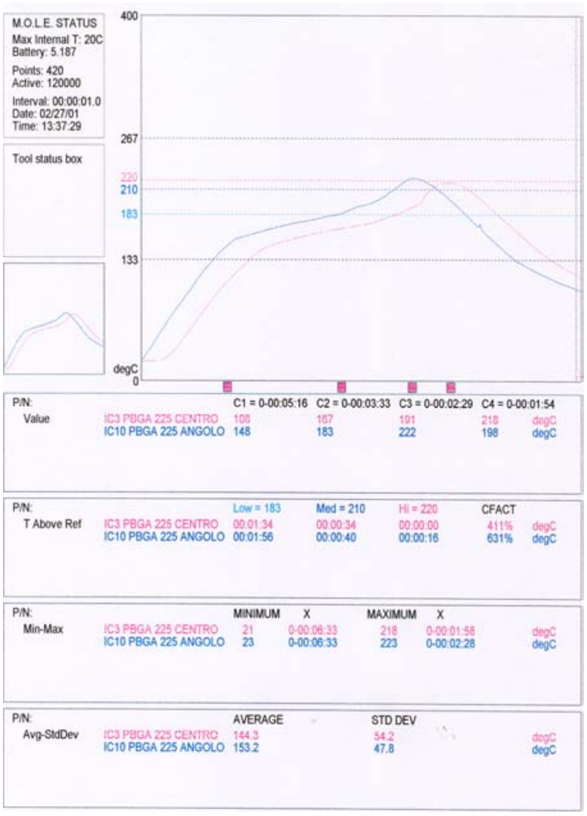


Figure 10 Experimental SuperMOLE thermo acquisition data

The tests have been carried out on a depopulated PBGA of 225 I/Os component typology, failed to the In Circuit (IC) test. The IC test serves to verify the defectiveness presence of no electrical contact or short-circuit. This investigation give positive results on the whole set of PCB. However, this type of inspection does not allow to investigate about the causes of the eventual heating defectiveness.

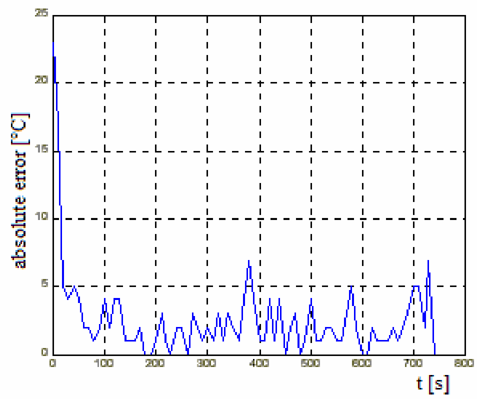


Figure 11 Absolute error on the center balls

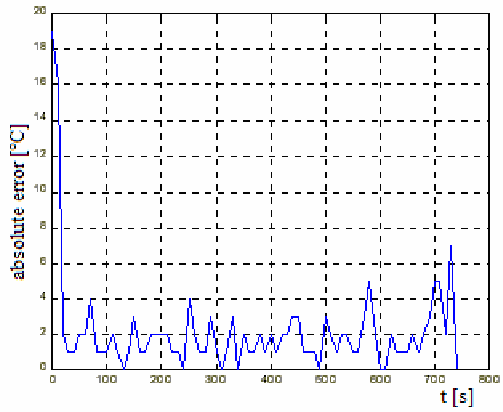


Figure 12 Absolute error on the corner balls

To investigate over, it is used the X-rays investigation [8]-[11]. The final X-rays analysis of a reworked component with the above suitable control parameters is shown in Fig. 13. Especially, there are not phenomena of short circuits or solder intrusion between the connections. This demonstrates that the thermal profile of the rework machine, obtained through the control parameters planning, reproduces the solder joint thermal profile of the reflow oven.

The parameters are stored in the scheduling program to be used for the rework of the components that have similar thermal characteristics.

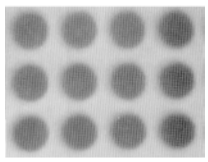


Figure 13 X-Ray after the rework process

7. Conclusions

A new approach has been introduced for the control parameter identification of the thermal solder join profile of BGA packages based on the scheduling planning of the relative Discrete Event Control System.

In particular, a saddle shape of the controlled quantity is the result of the simulation. In the saddle shape three regions can be distinguished: a) the initial region, that increases the temperature of the balls with the maximum gradient constraint; b) the flat zone, that serves to maintain the temperature with almost a null gradient (the thermal inertia mass of the considered component balls in this zone balances the quantity of dissipated and absorbed heat); c) the final peak, which confers the necessary quantity of heat to bring all the balls to the remelting temperature, subject to some constraints.

The experimental thermal profile is general purpose and can be applied to a wide typologies of components, also placed in different positions. In fact, empirical determination of different BGA parameters is possible by acting either on the permanence time or on the temperature of the three zones. The experimental results clearly demonstrate the advantages of the proposed approach.

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