Design, Fabrication and Testing of a Prototype Reflow Monitoring System (RMS)

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Abstract - **This research work relates to the soldering process observation in reflow ovens. The need for full continuous monitoring of reflow processes is more and more in the electronics technology. Today process monitoring of reflow soldering is based on temperature curve as a minimum requirement. A real time video observation functionality which allows control the flow of product through the reflow oven, this feature can make a very powerful control system. Based on this need for full process control, it has been developed a prototype system for visual monitoring of soldering process in an inline reflow oven during operation. The developed reflow monitoring system (called RMS) is able to pass through the reflow oven whilst observe and record video of solder joint formation on the printed circuit board assembly (PCBA). The RMS continuously can transfer data through WIFI connection to mobile phone as well.**

I. INTRODUCTION

One of the most important steps is the soldering by manufacturing of electronic circuits. The soldering provides a diffusion layer between the metallic parts and the printed wiring board [1]. The convection inline reflow ovens are typically used in the industry for soldering, but they are inside not readily viewable to the assembly line operators. The reflow process has many factors, where the accurate parameterization, control and monitoring are mandatory in the electronics field [2]. Generally, the reflow oven process control is based on temperature profile as a minimum requirement. The aim of this research work is to develop a real time video observation functionality (beside the temperature control) which allows visual control the flow of product through the reflow oven during operation.

Fig. 1. Reflow oven

That is why is so important to create a system where the soldering process can be observed accurately in the convention oven (Fig. 1) and the ongoing process can be recorded [3], [4]. This observation is supported with the developed video-based *"Reflow Monitoring System"* - called *RMS*. The RMS can get a clear picture of the soldering at each stage of the processes taking place. The external factors influencing the soldering can be examined using RMS. Quality of soldering can be improved and soldering defects will be more understandable [5], [6] using a real-time visualization in reflow oven.

II. STATE OF THE ART

Based on the available literatures, there are outer and inner video monitoring possibilities to follow a reflow soldering process. The outer video monitoring means an offline station, the inner monitoring is a special tool which travelling through the reflow oven during the soldering process.

Outer video monitoring: In the recent years the rework stations were used to follow and record the reflow processes [7]. Its open structure and controllable heating system gave the possibility for applying an external camera system, see "120" on Fig. 2. The video camera "120" can be focused, and the contrast and brightness levels thereof can be adjusted.
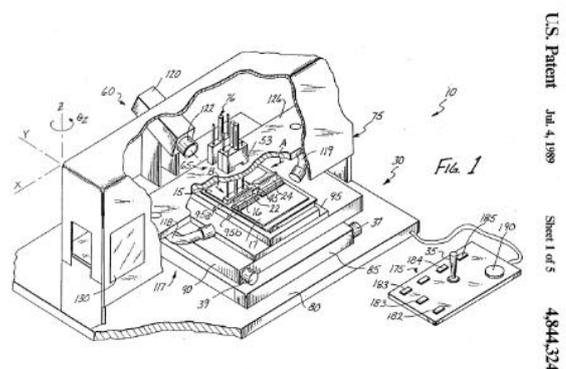

Fig. 2. Rework station

There are one zone reflow ovens beside the rework stations. The upper side of a one zone reflow oven is covered with glass, through this with a high optical zoom,

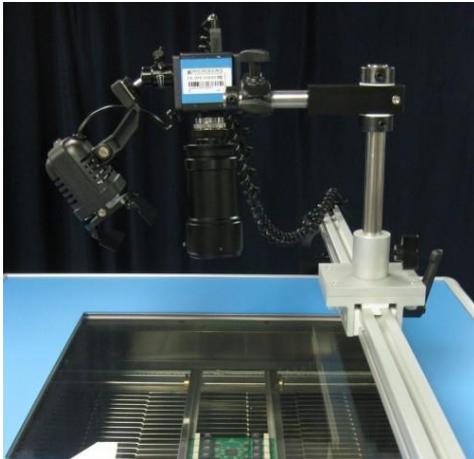wide-angle camera can record the soldering process (Fig. 3).

Fig. 3. PRO 1600-RS Reflow simulator

ATCO PRO 1600-RS is specifically configured for reflow simulation, package qualification, and thermal stress testing applications. Instead of performing reflows in an inline reflow oven, the batch design of this reflow simulator enables processing on a compact footprint. All while maintaining profiling flexibility, control, and consistency of a production in reflow oven.

Inner video monitoring: The soldering process inside the reflow oven can be checked in real-time using boroscope [8], which is available in full length of the oven (Fig. 4).
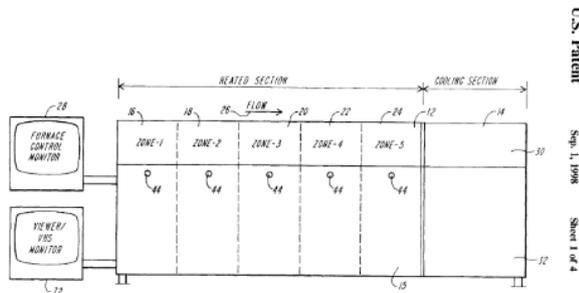

Fig. 4. Boroscope in reflow oven

The TMR from Malcomtech Company was the first equipment, which was able to monitor in video-based way the reflow process inside reflow oven [9], and not only from outside (Fig. 5.). The Malcomtech system is suitable for reflow monitoring, but its resolution is only 0.4 MP, which is insufficient by observation of small electronic components. Its fixed design provides little opportunity, suitable for video monitoring, but there is no build-in WIFI connection for online visualization and its price is also not favorable. Main focus of this research was to develop a reflow monitoring system that can be compared to this ready TMR, manufactured cheaper and its viewing angle and resolution are better than Malcomtech system. This developed RMS system was specially designed for our Hungarian Industry Partner.
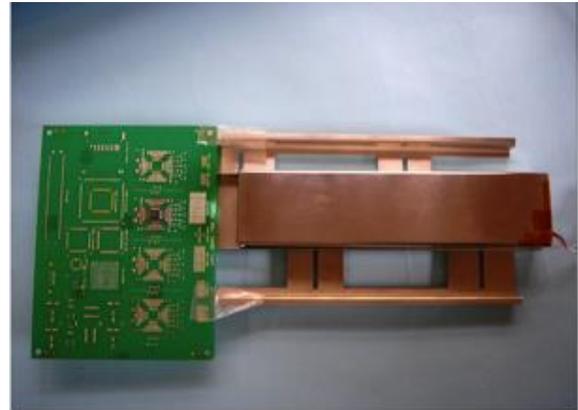

Fig 5. Total Monitoring System (TMR) from Malcomtech Company

The basic idea of an inner video monitoring system is visible on Fig. 6. A camera system is placed in a heat-resistant box travelling through the reflow oven together with the examined electronics assembly. The RMS initial parameters were agreed with our industry Partner in advance:

- Type of oven: reflow oven
- Camera system: HD resolution
- Peak temperature in reflow oven: max. 300°C
- Full cycle time: max. 10 min.
- Inner size limit of reflow oven: max. 30 mm
- Max. PCB width: 200 mm
- Flux residue resistance
- Dark environment

Fig 6. Reflow Monitoring System Concept
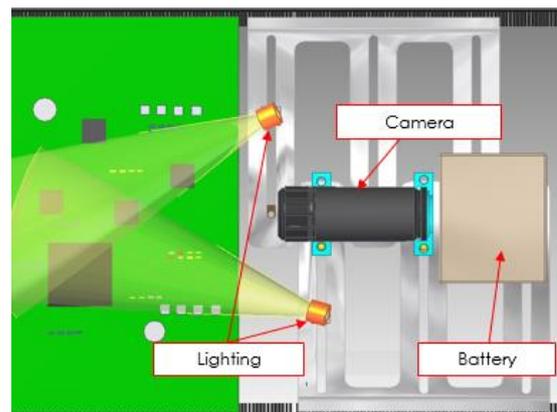
The RMS is primarily designed to monitor the formation of solder joints during reflow, but it can be used to solve soldering issues of the existing joints. To protect the electronics of the camera system inside RMS maximum internal temperature of 60°C was determined. Each subunits of RMS were designed, experimentally and analytically also verified using thermal management theory.

III. THERMAL MANAGEMENT

The method of final differences was used for the thermal calculation of RMS developed by M. A. Mihejev [10]. The main problem of the analytical solution of a transient heat conduction is the initial conditions and their relationships. Those are applying a significant simplification in each case. Consequently, in most cases it is not about a solution of differential equations, it is more a simplified, steady (stationary) stated model. Such calculating tasks can be solved using the final differences method made by M. A. Mihejev.

This method is based on that the continious process will be replaced with step-like process in time and space. For this purpose the heat conduction differential equation will be changed to an one-dimensional temperature distribution is as follows:

$$\frac{\Delta t}{\Delta \tau} = a \frac{\Delta^2}{\Delta x^2} \qquad (1)$$

The application was applied for flat, cylindrical and spherical bodies, as well as the determination of the two-dimensional temperature distributions worked out by E. Schmidt. In this case, the specimen wal (and RMS as well) is composed of different material and thickness of layers. These various quality layers are separeated into more equal thickness „Δx" stratify, which will be marked with $(n-1)$, n, $(n + 1)$, ... numbers. Similarly, the time intervals „$\Delta \tau$" decomposed upon k, $(k + 1)$, ... So „$t_{n,k}$" is the temperature of layer „n" in the middle and „k" represents the time interval, thereby forming the temperature curve in a broken line, which is shown in Figure 7:
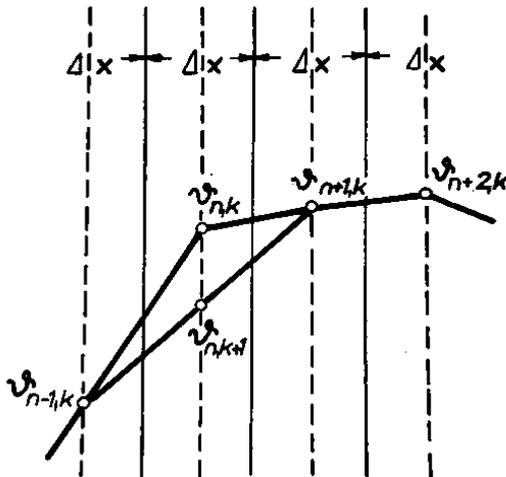

Fig. 7. Final differences method [1]

Figure 7 shows that the „n^{th}" layer in the temperature curve has two inclination angles. For this reason, the temperature difference has two coordinate values:

$$\left(\frac{\Delta t}{\Delta x}\right)_+ = \frac{t_{n+1,k} - t_{n,k}}{\Delta x} \qquad (2)$$

$$\left(\frac{\Delta t}{\Delta x}\right)_- = \frac{t_{n,k} - t_{n-1,k}}{\Delta x} \qquad (3)$$

Based on this for the second difference getting the following expression:

$$\frac{\Delta^2 t}{\Delta x^2} = \frac{1}{\Delta x}\left[\left(\frac{\Delta t}{\Delta x}\right)_+ - \left(\frac{\Delta t}{\Delta x}\right)_-\right] =$$

$$= \frac{1}{\Delta x^2}\left[t_{n+1,k} + t_{n-1,k} - 2t_{n,k}\right] \qquad (4)$$

Temperature difference by time in the layer „n" is given:

$$\frac{\Delta t}{\Delta \tau} = \frac{t_{n,k+1} - t_{n,k}}{\Delta \tau} \qquad (5)$$

(4) and (5) equations subtituting into (1) the following equation is given:

$$\frac{t_{n,k+1} - t_{n,k}}{\Delta \tau} = a \frac{t_{n+1,k} + t_{n-1,k} - 2t_{n,k}}{\Delta x^2}$$

Which is recalculated:

$$t_{n,k+1} = 2a \frac{t_{n+1,k} + t_{n-1,k}}{2} - \left(2a \frac{\Delta \tau}{\Delta x^2} - 1\right) t_{n,k} \qquad (6)$$

Known heat distribution during time „k", based on equation (6) can be determined at time „$k+1$" the temperature distribution. It must be choosen the layer thicknesses and intervals based on those determined to meet the following equation:

$$2a \frac{\Delta \tau}{\Delta x^2} = 1 \qquad (7)$$

In this case:

$$t_{n,k+1} = \frac{1}{2}\left(t_{n+1,k} + t_{n-1,k}\right) \qquad (8)$$

What is the basis, the „$t_{n,k+1}$" temperature is the arithmetic mean of „$t_{n+1,k}$"and „$t_{n-1,k}$". The value of „$\Delta \tau$" interval is determined by the following formula:

$$\Delta \tau = \frac{\Delta x^2}{2a} \qquad (9)$$

For the analytical solution the value of „Δx" advantageously should be chosen, then it has to be edited the initial distribution of temperature. This is visible in Figure 8, broken line form is shown 0 1 2 3. If point 1 is connected point 3, point 2' is given. If point 2 is connected point 4, point 3' is given.

Fig 8. Transient heat transfer graphics solution for homogeneous flat wall [1]

By constructing the points 0' and 1' it has to be taken into consideration the impact of external media as well, to which points an external steering „R" is required. The ordinate of external steering „R" is given by „tf" temperatue, its x-axis is given by subtangent of $s = \frac{\lambda}{\propto}$. For this reason, it is necessary a MN extra line parallel to the surface, what is placed from the surface with $\frac{\Delta x}{2}$ distance. The section between "O" and "R" select the point „a" on the line parallel to the MN surface. This point will be connected to the point 2, given point 1'. The initial distribution of temperature is given by points 0 '1' 2 '3.' With this method can be plotted further points 0'' 1'' 2'' 3'' 4'' after „Δτ". In case of multi-layer walls, the temperature curve can be constructed on the scale of thermal resistors. Then, instead of „Δx" shall be entered the abscissa Δx / λ value. The weak point of this procedure is the examined body and its the physical properties are noted constant.

IV. DESIGN AND FABRICATION

The first step in planning was the appropriate insulation material selection. Some oven tests were performed with help of a special test piece. The test piece was a 4 sided shape steel, one end was capped, the other end was sealed with silicon, which is shown in Fig. 9. Some insulating materials were selected to this experiment. Preliminary thermal conductivity calculation was performed on these materials, the heat radiation was neglected. For the experiments, similar to a reflow oven conditions were set, except that, a simple one-zone convection oven was used, where a set of 250°C has been exposed to the test materials for 10 minutes. The inside temperatue of sheet metal was registered during measurement. The space between the two steel shapes were filled with the variety of insulating materials.

Fig. 9. Test Piece for oven tests

The temperature conductivity of test piece and insulating materials in each layer were calculated. The calculation was based on specific heat capacity, density and coefficient of thermal conductivity of these materials. As a next step the individual layer thicknesses were measured. Each of the these layers were further divided into equal layer thicknesses. The time interval in seconds was determined using the following equation so, to be the same in every layer with different material properties:

$$\Delta \tau = \frac{\Delta x^2}{2a}$$

Value obtained by dividing the time interval of the experiment duration, which is determined for each insulation layer variations in the number of edits to be performed. Determined by the innermost temperature values obtained at the end of editing, which is worth insulating materials to carry out the experiments. Pyrogen most 2250, pyrogen-XT-10, basalt wool, carbon fiber and the air (air gap) materials were used in the calculations and experiments. The measurement results are shown in Table 1.

Table 1. Temperatures measured during oven test

Insulating materila	Peak temperature
Flame retardant pur	112,5°C
Air	*110°C*
Carbon fiber	100°C
Basalt fiber fleece (2 layers)	98,5°C
Basalt fiber fleece (1 layers)	78°C
Pyrogel-XT-10	71°C
Pyrogel-2250	59,5°C

Temperatures from the study were proportionate to the values obtained in the calculations, minor differences were observed, which confirmed the applicability of the method of M. A. Mihejev.

V.   CONSTRUCTION

There was a possibility to develop a thermal model based on the final differences method and oven tests. This model helped to choose the right materials and layer thicknesses for the roughly RMS construction. The RMS side walls of these layers form the outside towards to RMS interior: Stainless steel (0.5 mm) - air gap (1.5 mm) - Stainless steel (0.5 mm) - air gap (1.5 mm) - Pyrogel (2 mm) - Stainless steel (0.5 mm).
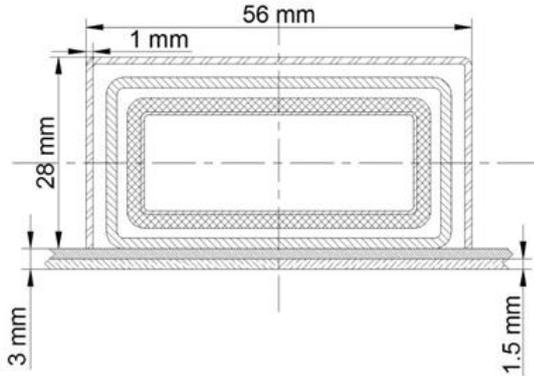

Fig. 10. Cross-section view of RMS

The two ends of RMS have different rolls. From one side the enough heat resistance has to be fullfilled, from other side there is a need for camera view in order to visualize the soldering process of the printed wiring boards. The end cup is build up with two materials, 10 mm PEEK and 10 mm Pyrogel 2250. The PEEK engineering plastics was choosen due to its high heat and chemical resistance combined with the superior insulation pyrogen 2250. The RMS closing side facing with printed circuit board, through which the soldering process takes place, is structured as follows: PEEK (2.5 mm) - heat-resistant glass (4 mm) - PEEK (5 mm) - heat-resistant glass (4 mm) - PEEK (2.5 mm) - stainless steel plate (2.5 mm). The thickness of the heat-resistant glass is to be accounted the effect of refraction of the glass and distorting.
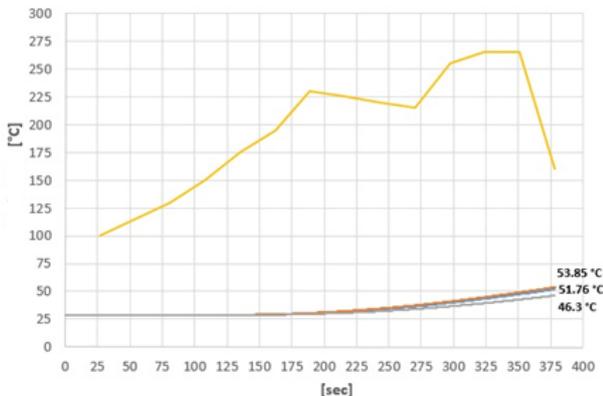

Fig. 11. Calculated internal temperatue of RMS

The thermodynamic calculations were three directions, the radial, axial direction and from the direction of the closing elements. Based on the calculations of the structure the warmest point will be the the closing element facing with the PCB. It is expected to be the RMS internal temperature of 53.85 ° illustrated on Fig. 11.

VI.   TESTING

The RMS has been tested in 14-zone convection reflow oven. Monitoring the temperature in a total of 4 thermocouples (TC) were used connecting with M.O.L.E recording device (Fig. 12.). Each thermocouples were positioned so to measure the air temperature. The first thermocouple was fixed on the outer surface of the RMS for oven air temperature measurement. The second TC is placed after the first air gap from the outside. The third and fourth TCs were located inside the RMS, where the electonics of RMS placed, between the two closing elements.

Fig. 12. Thermocouples with M.O.L.E

There was set a leadfree thermal profile on the reflow oven. The RMS together with M.O.L.E. (data collection system) travelled through the reflow oven within 378 seconds. After completing the experiment, M.O.L.E. data extracted from the recorder, result is show on Fig. 13.
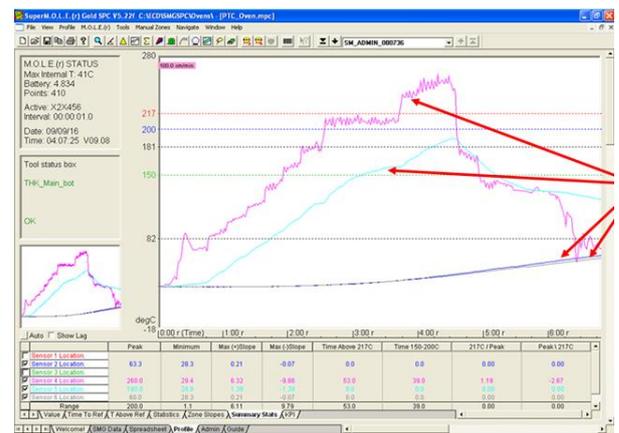

Fig. 13. Measured internal temperatue of RMS

The RMS maximum internal temperature during the tests was 55°C, indicating a good equivalence with the value obtained in the calculation temperature 53.85°C. Both measured and calculated temperature values are below the 60°C corresponds to the maximum temperature of the initial condition inside the RMS.

VII. CONCLUSION

The developed RMS prototype is suitable for monitoring and recoring of solder joints in real-time on printed wiring boards travelling through a reflow oven (Fig. 14).

Fig. 14. Developed Reflow Monitoring System (RMS)

During testing, the maximum value of the internal temperature was 55°C, which is below the sub-assemblies of a permitted maximum of 60 °C temperature. There was a leadfree thermal profil set on reflow oven for RMS testing. The recorded video in real-time gave a valueable picture about the solder joints located on the PCB (Fig. 15.). The test showed, the system is able to send the camera picture via WIFI to a mobile phone. This application gives a real visual monitoring possibilty about the reflow oven. It was clearly seen PCBA vibrations caused by conveyor during evaluation of recordings. Due to the method of calculation and experiment have managed to create a thermal model which modeled a similar heat transfer tasks and do not require further experimentation. Our goal is during the further development of RMS to reduce the internal temperature of the device and to increase the ability of the camera system.

Fig. 15. Real-time video in a reflow oven

ACKNOWLEDGEMENTS

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