A PROCESS MODEL OF THE INFRA-RED REFLOW SOLDERING OF PRINTED CIRCUIT BOARD ASSEMBLIES

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Abstract

This paper presents the latest results of an evolving model of the infra-red reflow soldering process. Recent additions to earlier models are the convective cooling of the PCB as it exits from the furnace muffle, and the addition of realistic component structures to the PCB assembly. The paper also presents the initial results from a second model of a high production volume, high quality, mass manufacture oven.

Introduction

This paper describes the most recent results of a major UK project jointly funded by the ACME directorate of the SERC and industry to generate an evolving model of the infra-red reflow soldering process within commercial reflow furnaces. Recent additions are the convective cooling of the PCB as it exits from the furnace muffle, and the addition of realistic component structures to the PCB assembly. The paper also presents the first of a second series of models which are being constructed of a more sophisticated oven appropriate to high volume, high quality, mass manufacture. The output from all of these models is a time temperature distribution for the assembly in question allowing the identification of heating and cooling rates in the assembly, the peak temperatures of the individual components and the time above reflow temperature for the solder joints.

Context

This work has been initiated with the aim of resolving the manufacturability issues that have arisen with the swing from through hole to surface mount technology. The chosen method of exploring these issues emphasizes the use of process modelling to examine the effects of the process variables on the quality of solder joint formation. Such models will facilitate the comparison of the temperature distributions within the printed circuit board and joint arena occurring for different layout and termination geometries and will also indicate the likely phenomena occurring in the soldering process.

The Evolution of the Computer Based Model

The model of the infra red reflow process is being developed on a network of Sun workstations using SDRC I-DEAS pre- and post-processing modules together with MAYA Heat Transfer Technologies Thermal Model Generator (TMG) finite difference analysis. The model has been constructed from the 'outside inwards' to enable establishment of boundary conditions for the each level of model refinement. The feasibility of the modelling approach was demonstrated in [1] which described the modelling of a Surf Systems IRM150 reflow oven. The IRM150 oven is a belt conveyor infra red reflow oven designed to be primarily radiative in its heat transfer to the electronic assemblies, although there is a degree of convective heating and especially cooling due to the presence of fans. The first model contained a number of basic structures, i.e. the oven model consisting of the emitter array and the muffle side walls and, within this, a bare FR-4 PCB with elements representing all six, top, bottom and four edge, faces. A subsequent paper [2] indicated how this model could be extended to to allow simple two dimensional modelling of more complex board structures including the influence of fixturing. The paper [3] populated the board presented in [1] with a variety of single joint geometries consisting of a copper pad, a mass of solder paste, the component termination and a representative mass of component body thus allowing their comparison for manufacturability. An overview of the above work is presented in [4]. The authors have also presented experimental results matching the model to observed materials behavior [5].

Improvements to the Model

It is the purpose of this paper to describe improvements to the models outlined above and to indicate the problems of applying this approach to the modelling of state-of-the-art reflow ovens.

Figure 1 shows the starting point for the models, an oven model capable of radiative heat transfer from three zones of the oven held at different temperatures. The purpose of these zones is to provide progressive heating of the PCB assembly in order to reduce variations in the PCB temperature and to keep the rate of temperature rise within the required limits.

The Addition of Convection

It was shown in [1] that convection is the principal cooling mechanism when the PCB exits from the oven. It is therefore necessary to include convective cooling in the model in order to be able to accurately predict the cooling rates and the time above reflow temperature. A forced convective cooling model has therefore been added to the model of the IRM150 oven. The convection is modelled using linear conductances whose values depend on the areas of the elements of the PCB they are associated with and these conductances link the PCB with a "heat-sink" at the factory ambient temperature.

Two complications arise in the addition of forced cooling to the model. Firstly, the cooling has to be synchronized with the furnace profile and applied such that it commences at the leading edge of the PCB and then progressively acts on an increasing area of the PCB. Secondly the air velocity provided by the oven cooling fans is not known and therefore the convective cooling coefficient has had to be determined by empirical calibration of the model with the results of experimental observations.

Figure 2 shows the effect of varying this coefficient on the cooling of
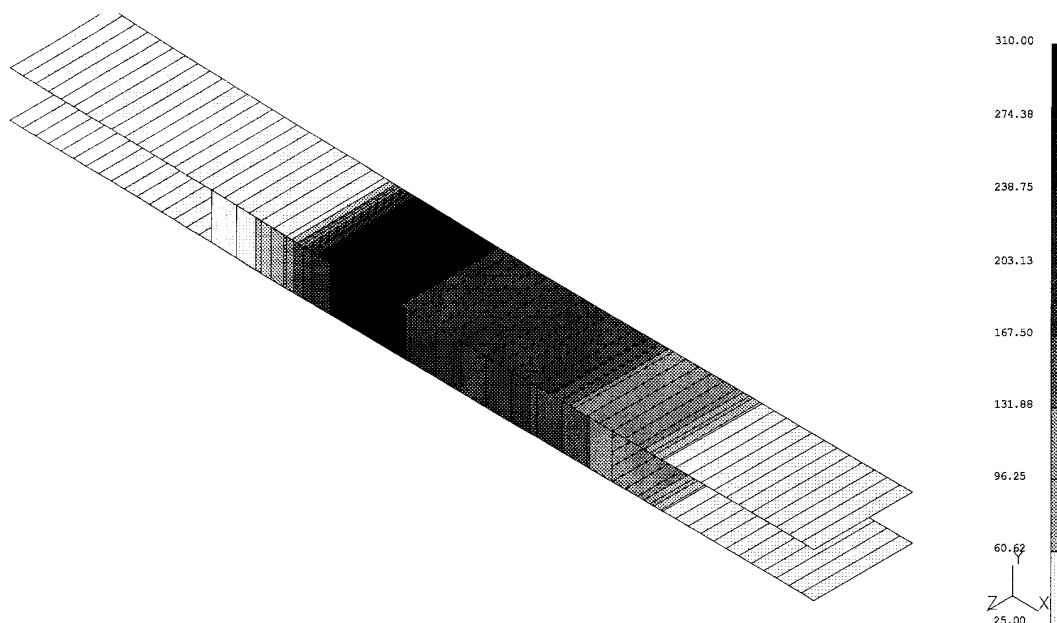
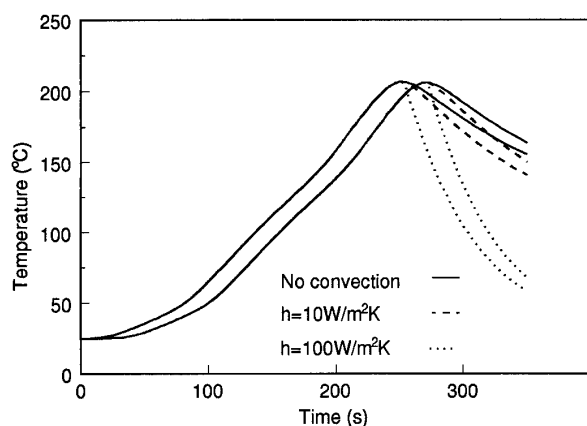Figure 1. Oven Model Including Multiple Temperature Zones.

Figure 2. Output of Model Showing the Addition of Convective Cooling With Two Values of Convection Coefficient..

the PCB. The figure shows curves for the leading (right hand) and trailing edges of the board.

The Modelling of Three Dimensional Component Structures

In order for the models being developed to be useful in PCB design and process validation it is necessary to be able to accurately model the whole of a complex PCB assembly perhaps containing several hundred components. Because of the finite limitations of computer processing power and disk storage space it is impossible to model such an assembly at a level of detail that includes the individual terminations and solder joints of each component on the PCB. It is therefore necessary to use a modelling technique which lumps the properties of the components into a simple representation which nev-

ertheless embodies the important thermal characteristics. This has been achieved by creating a single thermal mass representing the whole of the component together with a "shell" structure which represents the surface of the component available to radiative and convective heat transfer. This shell structure typically consists of five quadrilateral elements forming a box with its open side towards the PCB. This structure representing the component is then linked to the PCB through a heat transfer coefficient which is currently determined empirically, but it is anticipated that it will be possible to determine the coefficient using more detailed models of the component-termination/solder-joint/PCB-pad such as those described in [3].

Figure 3 shows the temperatures observed during the simulated passage of a board through the furnace. The board is populated with a number of structures equivalent to a variety of standard component types e.g. 16, 20 and 28 pin SO and various PLCC's.

The Modelling of a Mass Manufacture Oven

The IRM150 is a relatively simple and low cost oven, and it is important to be able to demonstrate the modelling of the features of a more sophisticated and high throughput machine. A large Senju furnace is therefore also being modelled as part of this investigation. This is a conveyorised infra-red/convective reflow oven incorporating edge heaters and six separately controlled heater zones. The addition of convection is intended to give a more uniform heating of the PCB by reducing the effects of emissivity variation and shadowing on the heat transfer. The oven comprises a total of twelve heater panels, six below the conveyor supporting the printed circuit board and six above. Convective heat transfer is achieved with the aid of air blown through the porous infra-red heater panels by a system of ducts and fans. The rate of convection can be controlled by regulating the the volume, temperature and velocity of air present. The heater panels themselves are spaced a short distance apart to give good circulation of the convective gases and allow its exhaust. Figure 4a shows a
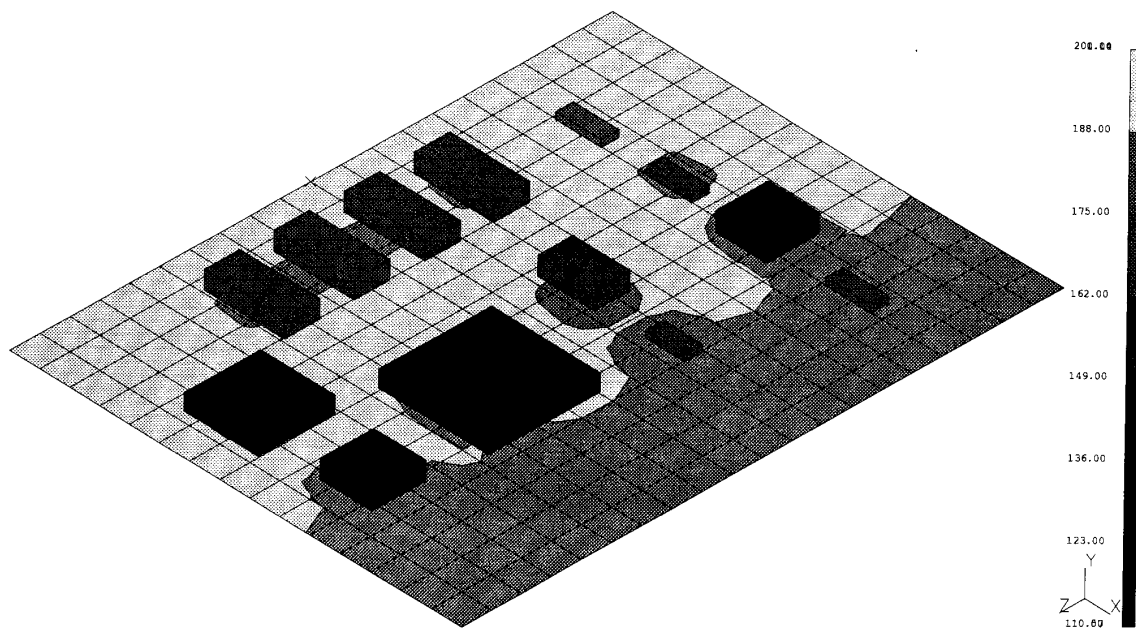
Figure 3. Simulated Temperature Distribution at One Point in the Reflow Cycle.

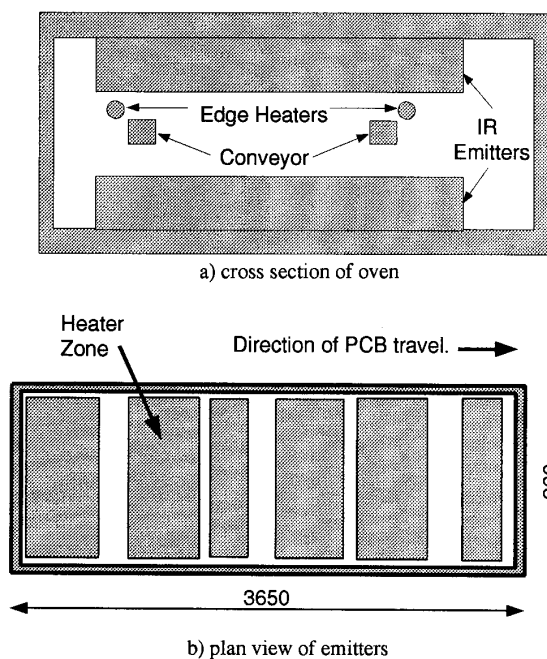
a) cross section of oven

b) plan view of emitters

Figure 4. Senju Oven Design

cross-section of the oven indicating the position of the board conveyor and edge heaters. Figure 4b shows a plan view of the arrangement of the emitters within the oven.
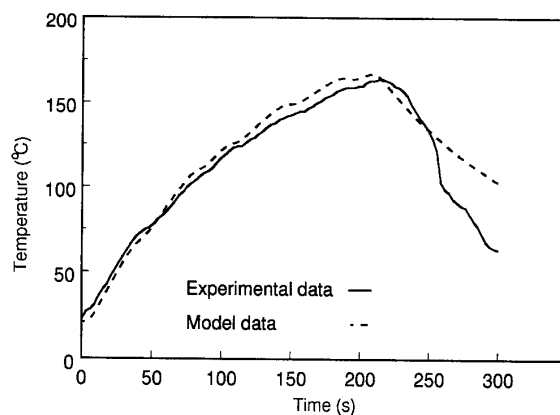
Initial modelling of the Senju Furnace

Since the geometry of the Senju furnace is significantly different to that of the IRM150 a new model of the oven muffle was required. The much larger height to width ratio of the Senju means that the side walls of the muffle play a negligible part in the heat transfer and so they were ignored in the new model. The relatively large gaps present between the emitters of the Senju furnace mean that the furnace effectively has twelve zones including the final cooling zone. Modelling this large number of zones was however a fairly simple extension to the modelling technique developed for the IRM150. The modelling technique used to simulate movement of the PCB through the furnace was also the same as that developed for the IRM150[1]. Figure 5 shows a comparison of the results from using this purely radiative oven model with a eurocard size test board together with experimental observations of the eurocard PCB in a real Senju furnace with all convective heating turned off. Notice the steps in both the observed values and the model due to the spacing of the infra-red emitters.

Figure 5. Comparison of Model and Experimental Data.

Future work on the Senju Model

It is necessary to understand the effects of both convective heating and the edge heaters on the process. The primary issues in subsequent modelling activities will be the effective simulation of convective heating and cooling and also the resultant effect of the edge heaters on the overall model. Calibration of the model variables to reflect practical issues cannot be over emphasised.

It is required to resolve the effect of edge heaters to determine whether they solely compensate for heat loss through the conveyor or whether they supply additional heat to the edge of the board.

Further, it is usually considered that the proportion of heat transfer in such combined IR/convection ovens is from 70:30 to 90:10 convective : radiative heating [6]. Figure 6 shows the observed values of the temperature at a single point on a eurocard sized test board both with and without convection. The figure shows that the difference between the two curves is not dramatic as may be expected, with the only major difference occurring in the second emitter zone and the overall temperature differences between the two profiles suggest that convection is only accounting for 20 to 30% of the heat transfer. The role of convection as an aid to more uniform heat distribution on the board however remains undisputed.
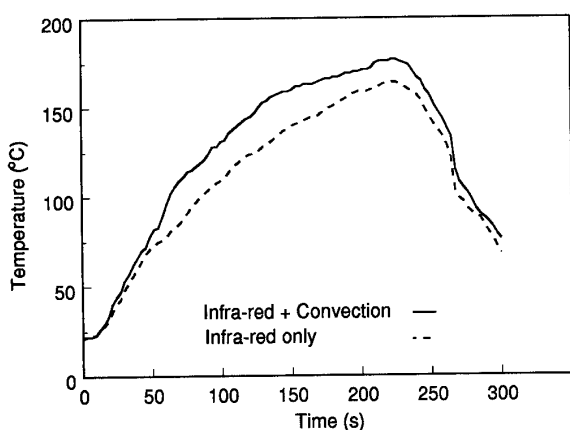

Figure 6. Oven Temperature Profiles with and Without Convection.

Concluding Comments

The closing stages of this work will expand the complex oven model to include the effects of edge heaters, and of convective heat transfer. In parallel with this activity an extensive programme of experimental studies to confirm and calibrate the models will be carried out.

References

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