DEVELOPING THE OPTIMUM REFLOW PROCESS: A MATTER OF COST AND QUALITY

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ABSTRACT
Learning the art of reflow profiling is a long, complicated road. Once mastered, it still requires significant time and effort. A new reflow profile should be developed for each new PCB, change in paste type, and/or the purchase or transfer of an oven. The profile development process requires dedicated knowledgeable personnel, allocation of materials, and inconvenient interruptions of the production schedule. The profile development costs are directly proportional to these factors. Profiling expertise is slowly learned via trial and error over a number of months. With time comes experience and with experience comes proficiency. Yet process optimization combined with cost minimization is never realized without the use of advanced profiling technology.

The solution to this costly learning curve is to utilize an Expert System which assists users in developing reflow profiles. The expert system, also known as AUTOset, captures the process engineer's experience and profiling expertise in a database. The profile database and commercial profiling software work synergistically creating in-specification or near specification reflow profiles. Creating profiles can be done with no prior process experience, and because the initial prediction is close, there will be relatively few, if any, additional profile runs to obtain a process that satisfies the product's manufacturing requirements.

This papers summarizes the development of the database as well as feedback from current customers in the areas of accuracy, time, and level of expertise

INTRODUCTION
A proprietary test vehicle was designed to simulate board types of varying complexity for the purpose of populating the database with different reflow profiles. This test vehicle, along with commercial profiling software, was employed to systematically optimize profiles for a variety of pastes, profile shapes, and board complexity. The database contains various types of profiles including those based on Sn/Pb or lead-free as well as linear or Ramp Soak Spike (RSS) reflow types.

The use of the database in conjunction with commercial profiling software has the following advantages for the end users:

- Shorten the process development learning curve,
- Be organizationally available to everyone to use and benefit from,
- Remains within the organization and it is not individual dependant,
- Reduces the time to develop profiles by minimizing the conventional pitfalls of the "first guess" at process setpoints,
- Provides a consistent approach, and does not require extensive process expertise to start developing profiles.

AUTOset makes it possible for the manufacturing engineer to accelerate process development by generating a preliminary reflow profile based on a PCB assembly's physical characteristics. The engineer can then 'fine tune' an optimized profile from the preliminary recipe if needed. This expert system effectively controls the these major elements in a reflow profile: ramp-up heating rate, thermal soak, time above liquidus (TAL), and peak temperature.

A group of five companies who are current users of AUTOset were interviewed. Customer visits, surveys, and analysis of predicted and actual profile recipes were carried out and the findings were summarized in his paper.

Development of the Database
Test Vehicle
A proprietary test vehicle was designed to simulate PCB types of varying complexity from simple 2-layer to 16-layer PCB's. The test vehicle was made of a thermal-resistant and robust material that was able to withstand reflow temperatures and multiple reflow passes without degradation. The performance of board was matched with actual PCBs behavior of different complexity and a relationship was established.

The database was populated with 176 reflow profiles using Vitronics Soltec XPM2 plus and XPM3 reflow ovens with 5, 8, 10, and 12 heating zones. It contains 5 process windows based on solder paste specification and includes 88 linear profiles, and 88 RSS profiles for a variety of board complexities. 36% of the profiles are lead-free and 64% are Sn/Pb. The board complexity was measured as a factor of assembly weight (g) and board area (inches^2).

Process Window Index
The criterion employed to evaluate the accuracy of both the predicted and validated profiles was the Process Window Index (PWI). The PWI takes into account measurement of the various reflow profile attributes and provides a single

number to indicate compliance with the specification or not to a what degree. A PWI value equals to or less than 100 is indicative of a profile that meets all reflow process specifications. A PWI value between 101 and 200 is indicative that at least one reflow process attributes is slightly out of specification. Examples of PWI's between 101 to 200 and the corresponding "out of specification" reflow parameter is listed in Table 1.

Table 1. Relationship of PWI Value to Actual Process Parameter Value

Calculated PWI	Peak Temperature Specification	Actual
101 + 10	245.0°C (maximum)	245.5°C
150 ± 10	208.0°C (minimum)	203.0°C
200 ± 10	208.0°C (minimum)	197.0°C

AUTOset takes into consideration the following reflow process attributes to evaluate the PWI:

- Maximum Rising Slope is the positive change of temperature per unit time. Typical specifications list a maximum of 3°C/sec. Defects associated with exceeding this heating rate are component damage, poor slump of solder paste, or adverse affects on the flux evaporation and activation characteristics.
- Thermal Soak is utilized to achieve an improved thermal equilibrium across the PCB. Thermal soak is defined as the time the PCB resides within a temperature range. The thermal soak part of the profile also allows for the activation of the flux and subsequent cleaning of oxides from all surfaces. Defects associated with exceeding the specified thermal soak time is deactivation of the flux and consequent poor solder joint formation.
- Time Above Liquidous is a defined range of time that the PCB is held at a temperature above the solder's melting point. Defects associated with insufficient Time Above Liquidous are poor wetting, incomplete joint collapse while defects associated with excessive Time Above Liquidous are formation of thicker, brittle intermetallic layers, potential failure of the board and components due to exposure, dewetting.
- Peak Temperature is the maximum temperature allowable for different components and solder paste. The combination of solder paste specification, component moisture sensitivity level (MSL), laminate requirements will limit the maximum possible temperature. Defects associated with exceeding peak temperature are the popcorn effect observed in components, delamination, cracking, lifting observed in the laminate.

An in-house evaluation was undertaken to gauge the accuracy and precision of predicted reflow profiles. In total, 56 unique profiles were predicted and then ranked based on the precision of the defined parameter specifications. These unique profiles were characterized by the selective combination of 11 different process windows applied to 7 different boards. Actual PCB dimensions ranged, on the low side, from 8.5"x6"x0.40" thick with a mass of 74 grams, to, on the high side, a board 17"x11.2"x0.125" thick with a mass of 1,260 grams. Validation of the latter PCB was accomplished with instrumented BGA balls to make the assessment more relevant and challenging.

The results show (Figure 1) that 55% of the validated profiles achieved a PWI less than 100. In these cases, the profile satisfied all process criteria. The second group of data contained 33% of profiles characterized with PWI's was between 101 and 200, which requires only one additional run to be on specifications.

While no trend is readily apparent, it can be concluded that 88% of the predicted profiles required either no further optimization or one iteration for the development of a robust reflow process.

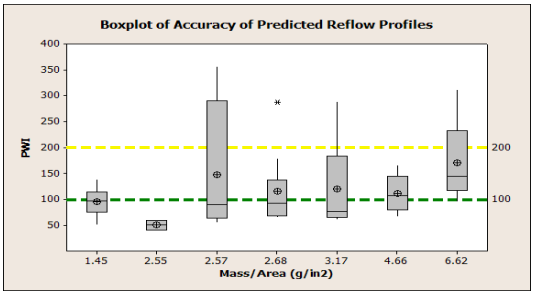

Figure 1. Accuracy of Proposed Reflow Profiles

Customer Feedback

A survey was carried out among five AUTOset users. A brief description of each company as well as their input is given below. For confidentially the company names have been changed to A, B, C, D, and E.

Company A

Company A purchased VS XPM3 820 ovens for the first time. It has a range of approximately 200 products, which need new reflow profiles because on their previous manufacturing practice, they used generic recipes. More than 4 new profiles are being developed in a week. They use more than 3 thermocouples to develop profiles and 3 people on their organization develop them. The profiles are developed for Sn/Pb and lead-free assemblies and the profile shapes are linear.

Before the use of AUTOset, it took between 1 and 2 hours to develop a reflow profile using the prediction tools on their current thermal data recorded. Typically a lead engineer having more than 5 year process experience would develop profiles.

They have started using AUTOset since May 2,009 for the development of all their recipes. On average,e the time to develop profiles has decreased as much as 50% and now technician with less than 3 months process experience are

developing profiles. Company A has reported that AUTOset predictions are very accurate. They typically will run just a confirmation run of the predicted recipe.

Company B
Company B is an EMS that purchased VS XPM3 1030 ovens for the first time. In average, 6 new profiles are being developed in a week for prototyping purposes. They use minimum 3 thermocouples to develop profiles and 4 people on their organization develop them. The profiles are developed for Sn/Pb and lead-free assemblies and the profile shapes are linear.

Before the use of AUTOset, they would use generic profiles for their products and trial and error approach to optimize their profiles. A lead engineer with more than 5 year process experience would be responsible for the reflow profiles.

They have started using AUTOset since March 2,009 for the development of all their recipes. The time to develop profiles is between 1 and 2 hours and now personnel with 3 months of process experience are developing profiles. They also mentioned that it takes in average 2 additional runs to optimize the predicted recipes.

Company C
Company C is an EMS that purchased VS XPM2+ 1030 ovens for the first time. Between 2 and 4 new profiles are being developed in a week. They use more than 3 thermocouples to develop profiles and 2 people on their organization develop them. The profiles are for Sn/Pb assemblies and the profile shapes are RSS.

Before the use of AUTOset, it took between 1 and 2 hours to develop a reflow profile using prediction tools on their current thermal data recorded. Typically a 5-year process experience engineer would develop profiles.

They have started using AUTOset since February 2009 for the development of all their recipes. It takes less than 1 hour to develop profiles and now technicians with 1 to 5 years process experience are developing profiles. Company C has reported that AUTOset predictions are very accurate. They typically will run just a confirmation run of the recipe.

Company D
Company D is an EMS that purchased VS XPM2+ 820 ovens for the first time. Between 2 and 4 new profiles are being developed in a week. They use 2 thermocouples to develop profiles and 3 people on their organization develop them. The profiles are for Sn/Pb and lead-free assemblies and the profile shapes are RSS.

Before the use of AUTOset, it took less than 1 hour to develop a reflow profile. They used a baseline recipe and tweaked according to their requirements. Company D stated that the profiles before AUTOset were not optimized resulting in quality issues and a lot of rework. Typically, a 3 month process experience person would develop them.

They have started using AUTOset since May 2,009 for the development of all their recipes. They have reported that the time to develop recipes is the same as before. They also reported an improvement of quality resulting in less rework.

Company E
Company E is an EMS that purchased VS XPM2+ 820 oven as a replacement for its VS XPM 520 oven. On average 3 profiles are being developed in a week. They use more than 3 thermocouples to develop profiles and 2 people on their organization develop them. The profiles are for Sn/Pb and lead-free assemblies and the profile shapes are linear.

Before the use of AUTOset, it took between 1 and 3 hours to develop a reflow profile. Typically a lead engineer would develop profiles, who has more than 5 years process experience.

They have started using AUTOset since January 2009 for the development of all their recipes. On average the time to develop profiles has decreased to 50%. Company E has reported that depending on the board complexity it may take up to 3 additional runs to optimize the profile.

Overall Results
The results of the survey indicated that 60% of the companies have reduced in 50% their time to develop new reflow profiles. They also indicated that before AUTOset, a 5-year process experience lead engineer would be responsible to develop reflow profiles. Now with AUTOset, 60% of the companies would assign a 3-month process experience personnel to develop new profiles and 1 company states that the expertise can be reduced to 1 – 5 years.

The accuracy of the predictions was measured by comparing the AUTOset predictions with the actual recipes as shown in Figure 2. The data was given by two companies. In the graphic, the PWI provided by AUTOset was compared to the PWI provided by the thermal profiler based on board complexity. It can be observed that from the 12 cases, 9 profiles were in specifications (i.e. actual PWI equal or less than 100). The first out of specification case corresponded to a Sn/Pb RSS profile (2.16 board complexity), the second one corresponded to lead-free linear profiles (3.66 board complexity) and the third one to Sn/Pb linear profile (4.76 board complexity). However, the PWI of these three are less than 200 which means that it would take less than 2 iterations to get profile on specification.

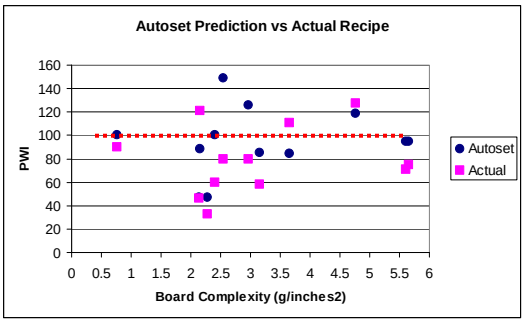

Figure 2. Comparison between Prediction and Actual Recipes

From the survey it was also found that 2 companies just run confirmation runs after AUTOset predictions while 2 companies run 2 more profiles to be in specifications.

It has to be noted that AUTOset provides a systematic approach to develop reflow profiles and is essential especially in situations where lack of process experience or time, costly material, or limited material supply are constraints that affect profile optimization, which is critical for the assembly of quality products.

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CONCLUSIONS

The advantages of data-based reflow profile prediction are significant to any electronics manufacturing organization large or small especially in situations where lack of process experience or material constrains for reflow optimization are found. AUTOset shortens the reflow profiling learning curve, reduces the expertise required to develop profiles, minimizes the number of iterations required to achieve an in-specification reflow profile, remains with the company - not just the employee, reduces the time required to start robust production, provides a consistent approach, and illustrates how science can be applied to what was traditionally held by the electronic industry as art.