Lead free wave soldering of simple to highly complex boards

Process optimization

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This research takes an in-depth look at the challenges encountered in developing a lead free wave soldering process based on the specific products as well as on specific materials. It attempts to provide the reader with the information necessary to make educated decisions in selecting materials and controlling various process parameters in order to execute a rational implementation strategy for a reliable and robust lead free wave soldering process.

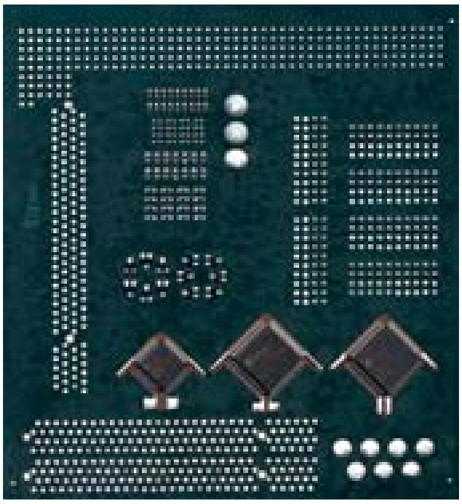

Figure 1: The GTLO board

Figure 2: A bottom side view of the Skate test vehicle

While previous iNEMI projects have focused on lead free joints soldered by the use of convection reflow ovens, since 2004, only a limited number of comprehensive investigations have taken place[1,2,3]. As a result, the lead free wave soldering project was developed in order to characterize and quantify the impact caused by the transition to lead free solder on the wave process itself as well as the impact on the performance and reliability of lead free solder joints. Within the board assembly chapter of the 2007 iNEMI roadmap the technology forecast[4] continues to provide consistent data on the nature of the wave soldering landscape. The issues today continue to be led by the enduring changes in materials and their maturity combined with a significant effort to minimize cost. Alloys containing silver adversely affect cost thus pressuring assembly houses to find alternative cheaper materials. Another pressure is the complexity of board technology. This results in an overall situation where materials are pushed to the limits of their respective specifications in terms of exposure to elevated temperature for extended times.

The lead free wave soldering project focused on three critical areas: Materials selection, process optimization and solder joint performance. In order to achieve these goals the project participants developed a two-phase approach. The companies supporting this project during the execution of phase I are Cisco Systems, Cookson Electronics, Delphi Corporation, Foxconn, IBM, ITW Kester, Jabil, Microsoft, Nihon Superior, Plexus, Solectron and Vitronics Soltec. The first phase of the project focused on characterizing process-related challenges and optimization of a lead free wave soldering process for various factors including: Fluxes, alloys, and board thicknesses. Characterizing the window of opportunity for various materials specifically designed for lead free assembly and its impact on wave soldering process is based on the quantification and analysis of specific defects.

The findings provide insight into the optimization of the wave soldering process for given material combinations. Confirmation of the data analysis was achieved by soldering boards utilizing the optimized parameter settings for the respective material combinations. The focus of this latter effort was to provide a data driven solution for the optimized wave soldering process which is an essential part of a robust and reproducible lead free assembly process.

The goal of the iNEMI lead free wave project is to ultimately characterize solder joint performance. Phase I provides the optimized settings that result in IPC class 3 acceptable through-hole fill for specific material combinations. Phase II of the project focuses on standardizing the lead free wave assembly process based on the phase I process development and optimization so that only solder joint performance will be evaluated. The intent of phase II is to provide the electronics assembly industry with timely and statistically backed understanding of lead free wave soldered joints. In order to achieve this goal, the team designed and fabricated a test vehicle that aims to understand future assembly requirements and consequently develop new standards and best practices for lead free wave soldering assembly. The board's name is GTLO (Get the lead out!). As shown in figure 1.

Experimental

In the design of this experiment a variety of materials were used. Criteria for the selection of these materials was based on industry assembly norms, gaps in information or industry need, and known reliability of specific materials not considered in the experiment.

Variable	Level 1	Level 2	Level 3	Comments
Atmosphere	Nitrogen	Air	N/V	
Belt speed ft/min (cm/min)	3 (91) 2 (61)	4.5 (137) 3.5 (107)	6 (183) 5 (152)	.062"/.094" .135"
Preheat Temp	90 °C 100 °C	110 °C 115 °C	130 °C 130 °C	(alcohol flux) (VOC free flux)
Flux Quantity	low	med	high	
Flux Type	Water	Alcohol	OA	
Chip Wave	on	off	on	
Solder Temperature	255 °C	265 °C	275 °C	
Board Thickness	0.062 (1.6)	0.094 (2.4)	0.135 (3.5)	Inches (mm)

Table 1: Definition of parameters and materials used for the inner array

Materials

Fluxes: Soldering fluxes are known to exert a significant influence on the resulting solder joint. Without performing a comprehensive flux investigation, three fluxes from three flux composition categories were selected.

1. No-clean alcohol based flux – 4.6 % solids content
2. No-clean water based flux
3. Organic acid water soluble

Alloys: The various, available lead free alloys on the market today consist of tin in excess of 95 %. As a result, the melting behavior of the alloys will be dominated by the melting point of tin, 232 °C. In this experiment three lead free alloys (SAC305, Sn100C, SACx) were selected based on project interest at the time the experiment was executed tin lead (SnPb) was also included to provide a benchmark to the majority of today's production lines.

Board: The test vehicle used in phase I was a Cookson Electronics designed test board referred to as the "Skate" board. The fabrication included the use of Polyclad 370 HR laminate with a 175 °C T_g and a high T_d. The layout of the Skate test vehicle used in this experiment included two types of through-hole components, four banks of passives, two banks of SOT-23s oriented in two directions, and three QFPs with varying lead pitch. A bottom view is illustrated in figure 2. Provided at the top of the board is a colour code of the four copper connection types designed into the test vehicle. The four connection types are:

1. No connection
2. Short spokes on wagon wheel
3. Long spokes on wagon wheel
4. Direct to ground

The colour code is followed in the schematic per through-hole. There are three locations for 120 pin PCI and twelve 20 pin dual row Berg Stick connectors. This was done in order to assess the impact ground plane connection to the barrel has on through-hole penetration. The green arrow indicates the direction of the board as it travels in the wave soldering machine.

Board finish was divided into two categories:
1. Cu OSP and 2. Alloy specific HASL

For each of the three lead free alloys and tin lead, the respective board finish was applied. That is, in the experiments where SAC305 alloy was used, the board finish was also SAC305 HASL. The OSP applied was Entek Plus HT.

The board thicknesses utilized in this experiment were 62 mils, 94 mils, and 135 mils.

Components

PCI Connector: One of the through-hole components selected was the 120 pin PCI connector with a lead free finish. This component was only available in one lead length. All three PCI connector locations were populated.

Berg Stick: The 20 pin dual row Berg Stick connector came in a lead free finish as well as a tin lead finish. The bottom side lead protrusion for this component was kept constant over the three board thicknesses by mechanical manipulation of the pins within the plastic housing. Seven out of the twelve locations were populated. Only one tin lead finished component was populated per board. The remaining six were lead free finish.

QFP: Three QFP sizes were used in this board design. Pad layout included solder thieves with varying design based on lead count and pitch.

- 64 lead – 0.5mm pitch
- 80 lead – 0.65mm pitch
- 64 lead – 0.8 mm pitch

SOT: A total of twelve SOT-23s were placed on each board. The twelve were divided into two groups of six. One group was parallel to the direction of board travel while the other group was perpendicular to the direction of board travel.

Passive Resistors: A total of four banks of passives were assembled onto each board. Two sizes were used including 0805 and 0603. As with the SOT configuration, the two banks of 0805s and 0603s were designed parallel and perpendicular to the direction of board travel.

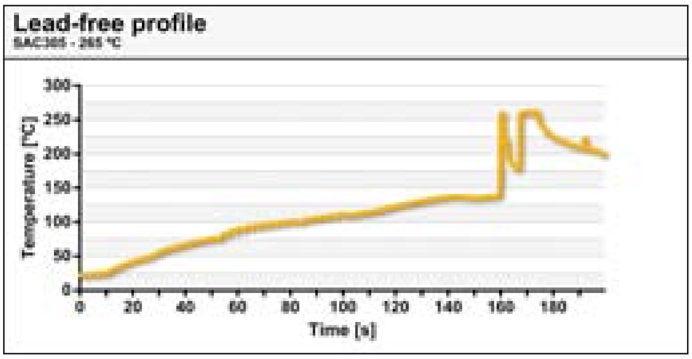

Figure 3: Typical lead free wave profile

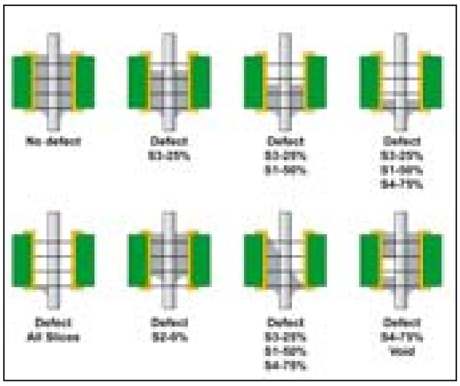

Figure 4: Data reporting scenarios for through-hole penetration based on 5DX analysis

Equipment: A Vitronics Soltec Delta 6622 wave soldering machine was used to assemble the boards for phase I. The wave soldering machine was configured with a dual head spray fluxer which was operated with a pump system and delivered each flux with specifically designed nozzles. The preheat technology and configuration for the three zones of preheat consisted of forced convection modules in the first two preheating zones and a calrod module in the last preheating zone. The wave configuration consisted of a chip wave and main wave. The chip wave is designed to deliver a turbulent flow of solder and the main wave is designed to deliver a laminar flow of solder. The nitrogen inerting system works on the blanketing concept and was operating at the following N_2 flow settings of 30,50, and 80 l/min. Parameter settings for each subsystem were controlled as required by individual runs in the design of experiments. All alloys were contained in individual solder pots that were switched out as needed to complete the DOE. This was done in order to eliminate any possible cross contamination issues.

Figure 5 A: Visual inspection of specific through-hole vias

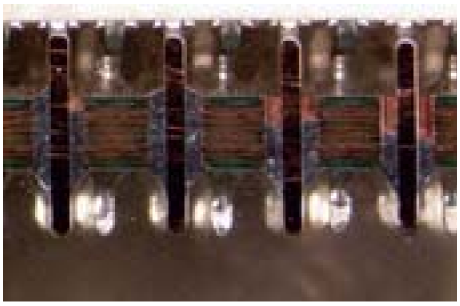

Figure 5 B: Cross sectional view of specific through-hole vias

Design of Experiment

The goals of phase I include ascertaining the relationship or influence of various parameters on the formation of defined defects; derivation and confirmation of an optimized process for each lead free alloy and board thickness. The team selected the Taguchi methodology to achieve these goals. During the development of the experiment a consensus was reached with eight parameters and materials placed into the inner array at three levels (listed in table 1). The four alloys and two board finishes were placed in the outer array. A Taguchi L18 orthogonal array was required for this set of materials and process parameters. The L18 was executed for each individual alloy and board finish resulting in a total of eight separate but comparable sets of data. Three replicates were assembled for each run.

The specific values of preheat temperature and flux quantity used in each run are based on the flux manufacturer's specification. Low and high settings are near the respective minimum and maximum of the recommended values and the medium setting is midway between to the two. The criteria used to determine the optimized process is based on the characterization of the through-hole penetration as per IPC 610D class 3 or 75 % hole-fill. The target was also consistent for desired hole of 100 %. Hole-fill was determined by 5DX laminographic analysis. Other defects such as shorts, solder balling, skips, and also solder shrinkage were visually characterized but not included in determining the optimized process.

Profiles: Characterization of the temperature profile and contact time was accomplished by using the ECD Mole profiler and the ECD WaveRider. Similar to the flux calibration, contact time and

Actual Run Order	DOE Standard Order	Atmosphere	Speed Ft/min (cm/min)	Preheat Temp	Flux Quantity	Flux Type	Chip Wave	Solder Temp. (°C)	Board Thickness (")	Sac 305	
										HASL	OSP
1	5	N_2	4.5 (138)	med	med	OA	on	255	0.062 "	0.0	0.0
2	1	N_2	3 (92)	low	low	Water	on	255	0.062 "	2.0	2.7
3	16	Air	6 (183)	low	high	Alcohol	on	255	0.094 "	41.0	44.0
4	12	Air	2 (61)	high	med	Alcohol	on	255	0.135 "	32.7	200.0
5	14	Air	3.5 (107)	med	high	Water	off	255	0.135 "	399.0	394.3
6	9	N_2	6 (183)	high	low	OA	off	255	0.094 "	48.0	44.3
7	10	Air	3 (92)	low	high	OA	off	265	0.062 "	0.0	0.0
8	2	N_2	3 (92)	med	med	Alcohol	off	265	0.094 "	3.0	0.0
9	15	Air	4.5 (138)	high	low	Alcohol	on	265	0.062 "	0.0	0.0
10	7	N_2	5 (152)	low	med	Water	on	265	0.135 "	358.3	350.3
11	6	N_2	4.5 (138)	high	high	Water	on	265	0.094 "	0.3	0.3
12	17	Air	5 (152)	med	low	OA	on	265	0.135 "	56.3	47.3
13	13	Air	4.5 (138)	low	med	OA	on	275	0.094 "	6.0	25.0
14	4	N_2	3.5 (107)	low	low	Alcohol	off	275	0.135 "	56.7	80.3
15	8	N_2	6 (183)	med	high	Alcohol	on	275	0.062 "	2.3	3.0
16	11	Air	3 (92)	med	low	Water	on	275	0.094 "	1.7	37.0
17	3	N_2	2 (61)	high	high	OA	on	275	0.135 "	58.7	55.0
18	18	Air	6 (183)	high	med	Water	off	275	0.062 "	1.0	1.0

Table 2: Through-hole penetration defect reporting for SAC305 on CuOSP and SAC305 HASL

preheat temperature were adjusted accordingly to ensure that the three levels of preheat and contact time were identical for each board thickness. Figure 3 illustrates a typical profile used to quantify topside preheat temperature and peak temperature on the Skate test vehicle.

Analysis: Various forms of analysis were employed in phase I. The reporting in this research is based on visual characterization of shorts and skips as well as x-ray analysis of hole-fill. Hole-fill was determined by using a programmed Agilent 5DX x-ray instrument. The data collection of barrel hole-fill was based on quarter percentiles. The types of defects observed are illustrated in figure 4. For the purposes of optimizing the process, only defects at the 75 % hole-fill or the top quartile were processed. However, increased sensitivity to process variations was provided by defects occurring at the various levels. This measurement was made on both the Berg Stick and PCI connectors. Select samples were cross sectioned to perform various analyses including hole-fill, barrel integrity, board integrity, and intermetallic formation. The procedure used to make these cross sections has been documented previously.[5]

ZUSAMMENFASSUNG

Diese Studie zeigt, wie entscheidend die einzelnen Wellenlötparameter zueinander in Beziehung stehen. Sie liefert die notwendigen Informationen, um fundierte Entscheidungen bei der Wahl einzelner Materialien treffen zu können und bietet Einblick in Arbeitsabläufe, so dass eine vernünftige Strategie zur Implementierung eines verlässlichen und robusten Wellenlötprozesses erreicht werden kann.

RÉSUMÉ

Cette étude montre l'importance du rapport existant entre les différents paramètres du brasage à la vague. Elle fournit les informations nécessaires pour pouvoir prendre des décisions fondées lors du choix de certaines matières et permet de visualiser le déroulement du travail de manière à pouvoir obtenir une stratégie raisonnable pour implémenter un processus fiable et résistant de brasage à la vague.

SOMMARIO

Questo studio mostra che la correlazione tra i singoli parametri della saldatura a onda ha un ruolo fondamentale. Offre le informazioni necessarie su cui basarsi per la scelta dei singoli materiali e permette di avere una panoramica dei processi di lavoro per definire una strategia mirata per l'implementazione di un processo di saldatura a onda solido e affidabile.

Results and discussion

The execution of phase I included the fabrication of the test vehicle, applying the correct finish onto the defined board thicknesses, procurement of the components, surface mount assembly and glue cure, flux procurement, and equipment setup. Once this was in place, a total of 324 boards were assembled per the Taguchi L_{18} orthogonal array experiment. The boards were visually inspected on site, followed by further inspection by professionally trained inspectors at an EMS, and then sent for the characterization of through-hole solder penetration by 5DX. As explained in the experimental section, the criteria employed to determine the output response was hole-fill greater than 75 %. In table 2, the results of x-ray analysis are provided for SAC305 on CuOSP and HASL finished boards. The same procedure was performed on the SACx and Sn100C runs. The defect data provided is the average number of defects per board as measured by 5DX. It is interesting to note that there are three runs which resulted in no defects while two runs resulted in hundreds of defects. The remaining runs are distributed between 1 defect and 80.3 defects. This provided the team with the distribution of data points that allows for a statistically significant determination of both process interaction and optimization. The behavioral analysis for the eight inner array parameters' influence on through-hole solder penetration for CuOSP finished boards is characterized by both linear or first order interactions except for flux amount which peaks at the medium amount. The derived optimized process for best through-hole penetration for SAC305 on CuOSP is:

- Atmosphere: nitrogen
- Transport speed: 3 ft/min
- Flux type: OA
- Flux amount: low
- Preheat temperature: 130 °C
- Chip wave: On
- Pot temperature: 275 °C
- Board thickness: 62 mil

The same analysis was performed for SAC305 on SAC305 HASL finished boards. The derived optimized process for best through-hole penetration for SAC305 on SAC305 HASL is:

- Atmosphere: nitrogen
- Transport speed: 3 ft/min or 6 ft/min
- Flux type: OA
- Flux amount: medium
- Preheat temperature: 90 °C
- Chip wave: on

References

[1] Gleason, J., Reynolds, C. "iNEMI Advanced Lead Free Assembly and Rework Project", April 2005.
[2] Hilman, D. et.al. "JCAA/JGPP Lead Free Solder Project" SMTAI, 2005.
[3] Holder, H. et. al. "Reliability of Partially-filled SAC305 Through Hole Joints" 2006 APEX Proceedings.
[4] See the Board Assembly Chapter of the 2007 iNEMI Roadmap.
[5] Marquez de Tino, U. "Procedure for the Preparation of Cross Sections" Vitronics Soltec information document.

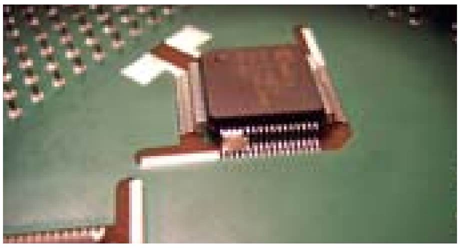

Figure 6 A: A five pin short on the 0.5 mm QFP

Figure 6 B: Close up of multi-lead bridging on a QFP

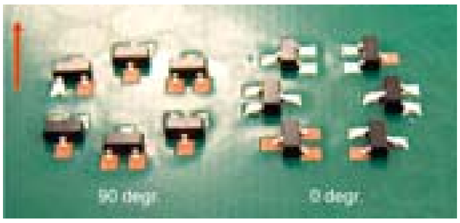

Figure 7: Board layout as per IPC and contrary to IPC design guidelines

- Pot temperature: 265 °C
- Board thickness: 62 mil

The intent of phase I was to develop and confirm an optimized process for three lead free alloys and on varying board thickness and board finish. Furthermore, the team regarded as a priority, developing a process that most resembled the majority of typical assembly methods utilized by project members. Based on this, it was not possible to select one board thickness or OA flux. The team elected to confirm the statistical model by soldering all board thicknesses (62, 93, 135 mils) with the no clean alcohol based flux. The derived optimized processes for the three lead free alloys is:

- Atmosphere: nitrogen
- Transport speed: 3 ft/min
- Flux amount: medium
- Preheat temperature: SAC305 130 °C/SACx and SN100C 110 °C
- Solder temperature: 265 °C

The only difference is the required topside preheat temperature of SAC305 versus both Sn100C and SACx. The former requires a temperature of 130 °C versus 110 °C for the two latter alloys.

Confirmation of the derived optimized process is required to ensure that the design and results of the L_{18} Taguchi experiment are valid. Upon finalization of the optimized process, confirmation runs were performed on the original lot of boards. Only HASL boards were utilized in the confirmation run since the OSP finish was compromised. Completion of the confirmation runs for each lead free alloy was successful after taking the proper precautions and PWB conditioning. Through-hole solder penetration was then measured using the same technique and criteria as in the analysis described for the L_{18} experiment.

The derived optimized wave soldering process for the three alloys (SAC305, SACx, Sn100C) were confirmed based on defect free soldering for the 62 mil and 93 mil thick boards. The 135 mil thick boards had minimal instances of less than 75 % hole-fill for each of the alloys. Overall, it is possible to conclude that the L_{18} Taguchi experiment was successful in providing the data needed to develop an optimized process for a variety of materials including flux type, alloy type, and board thickness.

Observations and trends

The following section provides some insight into various industry questions, challenges, and wave soldering assembly defect trends.

- **Impact of component design on through-hole solder penetration**

Although the Skate test vehicle only had two types of through-hole connectors, sourcing the PCI connector with varying lead lengths was not possible. As a result, the PCI connector lead protrusion changed as a function of board thickness to the extent that no lead protrusion was observed on the 135 mil thick card. A direct correlation was observed between through-hole solder penetration and lead protrusion. An inverse relationship exists wherein as the lead protrusion decreases, defects increase.

- **Impact of board construction on through-hole penetration**

The Skate test vehicle was designed with specific barrel tie-ins consisting of varying amounts of copper as defined in figure 2. This investigation collected and analyzed the impact of copper connection to through-hole solder penetration. Figures 5 A and 5 B illustrate the impact of a marginal wave soldering process on through-hole solder penetration. Figure 5 A provides a topside view of the PCI connector through-holes which is visible to the inspector while figure 5 B provides the cross sectional view which allows one to measure actual hole fill. Moreover, the influence of copper tie-ins to the barrel is observed in one of the L_{18} runs. In these images the barrel construction is described from left to right as short spoke on wagon wheel, no connection, long spoke on wagon wheel, and direct connection. In the cross sectional view it is possible to determine that the long spoke wagon wheel (3rd from the left) and direct connection (4th from the left) have less then 75 % through-hole penetration. This behavior was observed regardless of alloy or board finish and is mainly dependent on two factors: Wave soldering process and board complexity/construction.

- **Impact of QFP pitch on bridging**

Based on the visual inspection data collected after the assembly of the 324 boards, it was possible to determine some empirical trends on QFP bridging. Figures 6 A and 6 B illustrate two instances of shorts occurring on a QFP. The analysis of the bridging occurrence clearly provides the challenge one has in assembling QFPs with pitches less than 0.65 mm. All alloys were characterized by greater than 1000 leads with bridges on the 0.5 mm pitch QFP. Comparison between alloys is less definitive since it is observed that each alloy performed equal to or better than the other two for different QFPs.

- **Impact of board layout on skips**

The Skate test vehicle component layout included surface mount components aligned parallel and perpendicular to the direction of the board over the wave. In addition, the DOE inner array design focused on the utilization of the turbulent flow chip wave. Analysis of the visual data collected on skips in the area of SOT-23s, as shown in figure 7, provides insight into which parameter(s) are most critical in minimizing skips. As listed in table 4, the single most important parameter is the use of the chip wave. The turbulent solder flow penetrates the areas of the component lead/pad that are biased against proper wetting. Thus allowing for a proper joint to form.

Conclusion

This research provides insight into several of the key questions and challenges observed in today's lead free wave soldering process. The collaborative effort investigated process parameter and material impact on the soldering process and joint formation. All types of solder joints were produced ranging from highly oxidized, not solder-able surfaces to the optimum solder joints. The result of this investigation was to lay the foundation of a broader effort to characterize the performance of through-hole solder joints on a test vehicle specifically designed for testing the norms of tin lead wave soldering.

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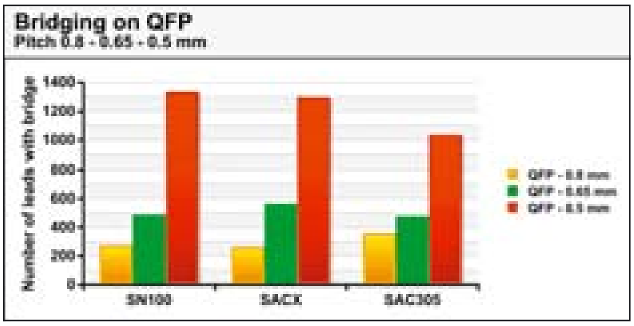

Table 3: Relationship of bridging to QFP lead pitch and alloy

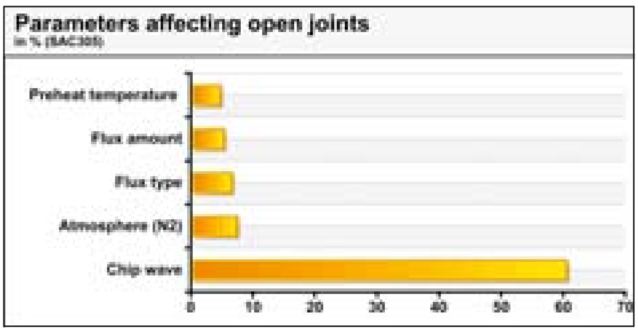

Table 4: The influence of process parameters on minimizing skips