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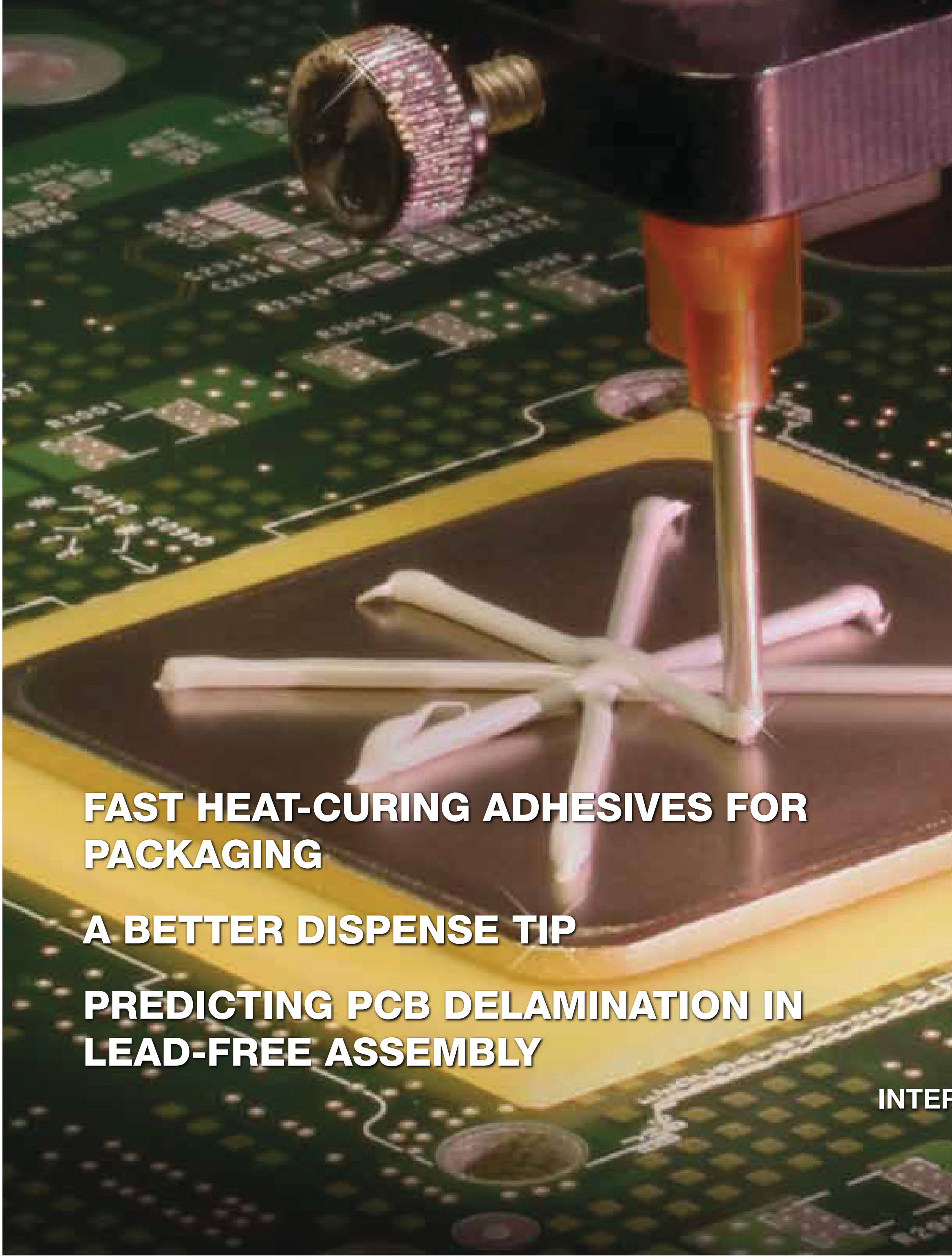

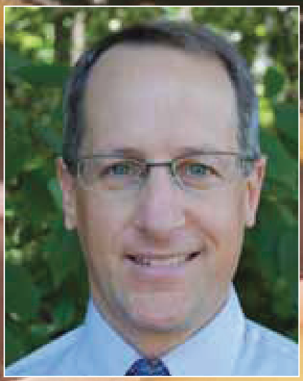

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Predicting PCB delamination in lead-free assembly

Geert Willems, PhD, and Piet Watté, PhD, imec, Heverlee, Belgium

Selecting the right FR4-type laminate for a lead-free solder printed board assembly (PBA) has become a critical but difficult task for the PCB designer. Modeling the decomposition reaction of epoxy and the associated pressure build-up in the PCB makes the delamination risk of a PCB during lead-free soldering predictable. The lead-free soldering compatibility of IPC-4101C /sheet categories is discussed. A quantitative FR4 laminate selection method is proposed.

Keywords: Printed Circuit Boards, Lead-Free Assembly, Delamination, Modelling

The designer's FR4 selection problem

Lead-free soldering of printed board assemblies (PBA) imposes several high temperature excursions on the printed circuit board (PCB) that may damage the laminate and/or the via-structures. The required number of solder cycles depends on the assembly complexity and the need for repairability of the PBA. New FR4 laminate types with improved lead-free soldering robustness have been introduced. The latest edition of IPC-4101C, *Ref. 1*, now specifies[1] 12 lead-free soldering compatible FR4 /sheets for which the parameters CTEz (thermal expansion), T_d (decomposition temperature), T260, T288 and T300 (time-to-delamination) are specified. Table 1 gives an overview of the soldering performance parameters for the different /sheet numbers.

The remaining designer's question is: "What type of FR4 laminate do I need for my printed board assembly?" At best empirical guidelines, *Ref. 2*, and recommendations of PCB and EMS suppliers are at the disposition of the designer. Unfortunately, this approach of selecting a laminate does not provide a quantitative risk assessment regarding lead-free assembly damage, nor does it give a direct method to determine the minimal values of the soldering performance parameters listed in *Table 1*.

This paper wants to remedy the situation. A method to determine the minimal values of Td, T260, T288 and T300 provided in IPC-4101C based datasheets to assure a certain number of solder-cycles-to-delamination is provided.

PCB failure mechanisms at lead-free soldering

New FR4 laminate types compatible with lead-free soldering addresses two major failure mechanisms:

- via barrel cracking caused by the difference in thermal expansion between the via copper barrel and the surrounding epoxy matrix (CTEz);
- cohesive failure (T260, T288, T300) of the laminate due to thermal decomposition (Td) of the epoxy matrix.

The latter is the subject of this paper. To be able to determine the number of solder cycles-to-delamination, the failure mechanism must be described quantitatively. The following delamination mechanism is proposed:

- During soldering, a fraction of the epoxy decomposes.
- The decomposition products create internal pressure in the laminate at elevated temperatures.
- During the next soldering step, the internal pressure will become higher than during the previous one due to pressure build-up caused by the already present and newly released decomposition products.
- The PCB will delaminate in the soldering cycle where the internal pressure exceeds the cohesive strength of the laminate.

In this elementary description, diffusion of decomposition products is not taken into account because:

- It is expected that the short high temperature soldering phase (a few minutes) and the short time between soldering operations (hours at room temperature) will not allow significant loss of decomposition products by out-diffusion.
- No loss of decomposition products is the safe, worst-case scenario condition that is representative for the centre portion of a PCB with large copper planes hindering diffusion.
- Laminate selection criteria should neither depend on design details, such as the copper distribution, nor on manufacturing details like the

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[1] IPC-4101C specifies also two non-FR4 lead-free compatible laminate classes in /102 and /103.

/sheet	99	101	121	124	126	129	122	125	127	128	130	131
Tg min (˚C)	150	110	110	150	170	170	110	150	110	150	170	170
Td min (˚C)	325	310	310	325	340	340	310	325	310	325	340	340
max. CTEz (%)	3.5	4.0	4.0	3.5	3.0	3.5	4.0	3.5	4.0	3.5	3.0	3.5
T260 (min)	30	30	30	30	30	30	30	30	30	30	30	30
T288 (min)	5	5	5	5	15	15	5	5	5	5	15	15
T300 (min)	AABUS	AABUS	AABUS	AABUS	2	2	AABUS	AABUS	AABUS	AABUS	2	2

Legend: orange - Bromine based flame retardant; green - low halogen; dark/pale - filled/non-filled

Table 1: Overview of the lead-free data sheets of IPC-4101C.

time between subsequent soldering steps. Therefore it is a realistic and conservative assumption to neglect loss of decomposition products due to diffusion.

To calculate the number of solder cycles-to-delamination we need the following:

1. A quantitative description of the decomposition reaction of epoxy.
2. A quantitative description of the concentration of decomposition products as a function of temperature and time to calculate the pressure build-up.
3. The relationship of the above with the soldering performance parameters Td, T260, T288, and T300 specified in laminate data sheets.
4. A standardised reflow-profile to calculate the number of solder cycles-to-delamination.

A quantitative description of the decomposition reaction

The thermal decomposition of epoxy at low decomposition levels can be written as in *Equation 1* with ρ, ρ0 the density of the remaining respectively original epoxy resin filler excluded, *k(T)* the temperature dependent reaction rate, k_0 a kinetic factor, E_a the activation energy of the decomposition reaction, *R* the universal gas constant and *T* the temperature in Kelvin.

The parameters E_a and k_0 of the decomposition reaction can be derived from a thermo-gravimetrical analysis (TGA) of the laminate per IPC-TM-650, 2.4.24.6. Such TGA measurements are used to determine the decomposition temperature T_d at 5% weight loss mentioned in laminate data sheets. For a constant TGA heating rate Φ the time dependence of the temperature *T(t)* becomes *Equation 2*.

Integrating *Equation 1* with a linear temperature profile (*Equation 2*) gives the TGA curve for a laminate with a resin content *RC* and a resin filler content *f* (*Equation* 3) where $E_i(x)$ is the Exponential Integral, *Ref. 3*, and $m_l(T)/m_l$ the relative change in laminate mass in the TGA experiment. Fitting *Equation 3* to experimental TGA values determines k_0 and E_a.

Quantitative description of the pressure build-up

The decomposition products will be located in the epoxy matrix but may also escape into pores between the fibres of the glass fabric or even be absorbed to an unknown level by the inert glass fibres and/or filler material. The details of this process as well as the composition and properties of the decomposition products are unknown but not essential to describe the delamination phenomenon. For the description of the pressure build-up in a laminate of volume V_l, mass m_l, resin content RC and resin filler content *f*, it is assumed that the pressure build-up of the decomposition products will follow an ideal gas law with unknown gas constant *r'* respectively *r* for the gas absorbed in the epoxy matrix respectively the gas residing in laminate pores. The available volumes for the gas are the resin volume $V_r=m_l(1-f)RC/\rho 0$ for the gas absorbed in epoxy and a fraction a of the volume of the non-epoxy material in the laminate $aV_{in}=a(V_l - V_r)$ for the gas residing outside the resin matrix itself. Assuming pressure equality and the conservation of mass, the internal pressure *p* as a function of temperature can be written as *Equation 4*.

The laminate will cohesively fail when a certain critical pressure *pc* is reached that exceeds the internal tensile strength of the laminate or, alternatively, when the quantity T_c, the delamination threshold expressed in Kelvin as described by *Equation 5*, reaches a critical value. The possibility of decomposition products to reside outside the resin matrix introduces a resin content dependency of the delamination threshold $T_c(f,RC)$. A higher resin content RC will create more pressure and therefore a lower threshold

Equation 1.

$$\frac{\partial}{\partial t}\left(\frac{\rho}{\rho_0}\right) = -k(T)\frac{\rho}{\rho_0} = -k_0 \exp\left(-\frac{E_a}{RT}\right)\frac{\rho}{\rho_0}$$

Equation 2.

$$T(t) = \Phi.t + T_0$$

Equation 3.

$$\frac{m_l - m_l(T)}{m_l} = \left(\frac{\rho_0 - \rho(T)}{\rho_0}\right)(1-f)RC$$

$$\ln\left[\frac{\rho_0 - \rho(T)}{\rho_0}\right] = \frac{k_0}{\Phi}\left[T\exp\left(-\frac{E_a}{RT}\right) - \frac{E_a}{R}\mathrm{E_i}\left(1,\frac{E_a}{RT}\right)\right]$$

Equation 4.

$$p = \left(1-\frac{\rho(t)}{\rho_0}\right)\frac{r\rho_0 T}{\frac{r}{r'} + a\left(\frac{\rho_0 V_l}{m_l(1-f)RC} - 1\right)} = \left(1-\frac{\rho(t)}{\rho_0}\right)\frac{\rho_0 T}{c(f,RC)}$$

Equation 5.

$$T_c(f,RC) = \frac{p_c}{\rho_0}c(f,RC) = \left(1-\frac{\rho(t)}{\rho_0}\right)T$$

Equation 6.

$$T_c(f,RC) = \left(1 - \frac{\rho_i(T_{TTD})}{\rho_0}\exp[-k(T_{TTD})t]\right)T_{TTD}$$

$$k(T_{TTD}) = k_0 \exp\left(-\frac{E_a}{RT_{TTD}}\right)$$

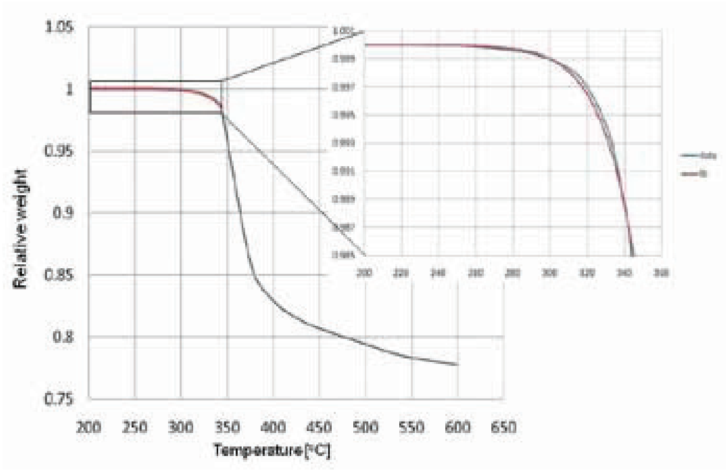
$T_c(RC)$. This explains why delamination predominantly occurs in the resin-rich pre-preg regions of the PCB.

Determining k_0, E_a and T_c from laminate datasheets

The delamination threshold T_c is reached at the time of delamination in a time-to-delamination experiment per IPC-TM-650, 2.4.24.1. Therefore T_c can be determined from such an experiment and thus from the time-to-delamination values specified in laminate data sheets if the decomposition reaction parameters k_0 and E_a that determine ρ(*t*) are known from the TGA experiment. Solving Equation 1 for the temperature profile used in a time-to-delamination (TTD) experiment yields *Equation 6*, with T_{TTD} the test temperature and $\rho_i(T_{TTD}) < \rho 0$ the epoxy density at the start of the constant temperature period of the TTD-test.

Ideally the parameters k_0, E_a and T_c are obtained from a fit of *Equation 3* to the TGA data set and a single time-to-delamination parameter e.g. T288 using *Equation 6*. Unfortunately, laminate datasheets contain insufficient TGA data to directly determine the decomposition reaction parameters k_0 and E_a. Therefore, these parameters need to be derived in conjunction with the threshold value T_c from the available parameters Td, T260, T288, T300 by simultaneously solving Equations 3 and 6. Variations between resin content of laminates used for TGA (Td– unspecified resin content per IPC-4101C) respectively used for TMA (time-to-delamination—resin content between 40 and 45% per IPC-4101C) analysis and incomplete time-to-delamination data limit the accuracy of the calculation based on laminate datasheet data.

As a demonstration of the model's predictive capability, *Figure 1* shows its experimental verification on a low halogen laminate material. Deriving the parameters k_0 and E_a from a fit to a TGA experiment, *Figure 1*, and a single time-to-delamination value T288 the values of T260 and T300 can be predicted in agreement with the



TGA, TMA analysis and modelling results

Td	350	[°C]
E_a	170	[KJ/mole]
k_0	8.1x10^{11}	[1/s]
T260 (aborted meas.)	>120	[min]
T288 measured	32.0	[min]
T300 measured	13.1	[min]
T260 predicted	236.4	[min]
T300 predicted	13.7	[min]

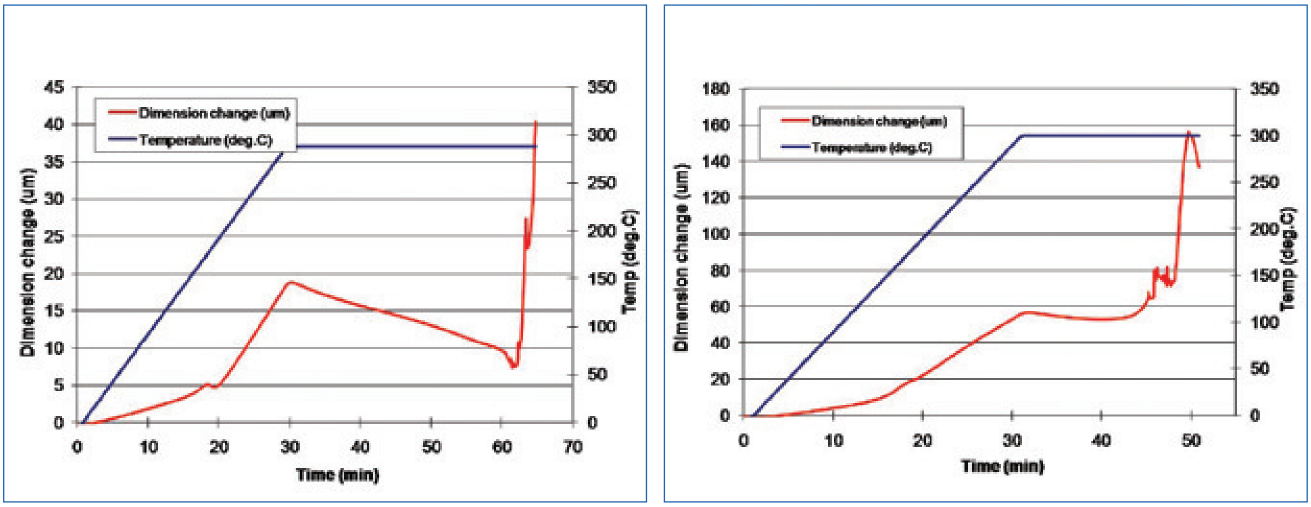


Figure 1. TGA and TMA analysis of a low-halogen laminate. Evaluation of delamination model by TGA model fitting and prediction of T300 (table & bottom right) and T260 (table) from measured TGA (top left) and T288 data (bottom left). Caveat: The TGA model assumes a low decomposition level therefore the TGA fit is ended at 8% decomposition of the resin i.e. about 2% TGA mass loss.

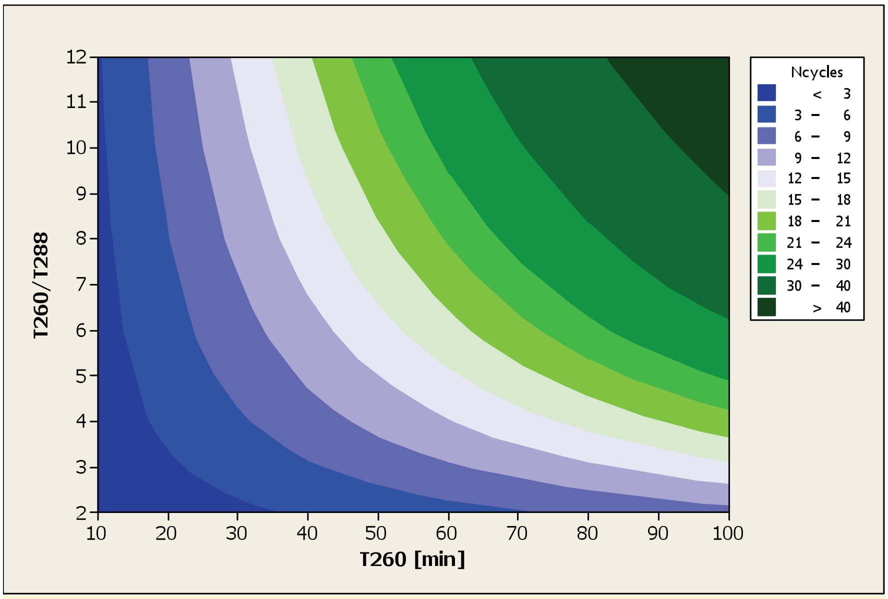


Figure 2. Number of solder cycles-to-delamination as a function of T260 and T260/T288.

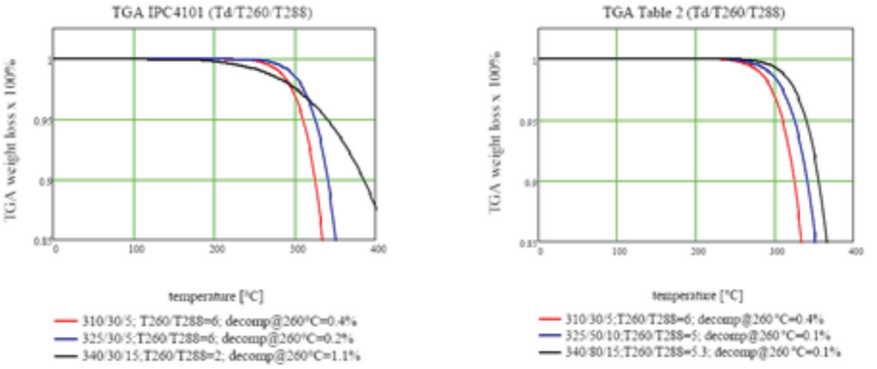


Figure 3. TGA curves for laminates satisfying the IPC-4101C boundary requirements versus the TGA curves satisfying the boundary conditions proposed in Table 2.

Category	Td (°C)	T260 (min)	T288 (min)	N_d	Compliant Classes
Basic	310	30	5	7	/99, /101, /102, /103, /121, /122, /124, /125, /126, /127, /128, /129, /130, /131
Mid	325	50	10	12	/99, /102, /103, /124, /125, 126, /128, /129, /120, /131
High	340	80	15	20	/120, /126, /129, /130, /131

Table 2. Proposed boundary conditions and associated number of solder cycles-to-delamination N_d *consistent with IPC-4101C laminate /sheet classification.*

experimental observations. From the measurement one can derive that the net resin content amounts to *(1-f)RC≈23%* consistent with RC=40-45% and a filler content of about *f*=50%.

A further confirmation of the validity of the model is found by observing that the delamination threshold T_c is related to the resin system including fillers and glass fabric. Therefore it is expected that FR4 laminates belonging to the same thermal performance class and with similar resin and filler content will have similar T_c values. This is confirmed by calculating T_c for several laminates for which sufficient information is available in the datasheet. Assuming a resin content in the range of 40 to 45% (42%) the unfilled laminates yield a delamination threshold in the range of T_c=23-24K (325°C>T_d>310oC, 2 laminates), T_c=25-29K (340°C> T_d>325°C, 3 laminates) and T_c=28-38K (T_d>340°C, 5 laminates). For the filled laminates we obtain T_c=51-57K (340°C> T_d>325°C, 6 laminates) and T_c=55-59K (T_d>340°C, 5 laminates) assuming a filler content of about 50%.

The number of solder cycles-to-delamination

To calculate the number of solder cycles-to-delamination we need a reference solder profile. A piece-wise linearised reference reflow profile is used that fulfils the J-STD-20D.1 component qualification requirements with peak temperature of T_p=260°C. The calculation of the number of solder cycles-to-delamination Nd consist of calculating the cumulative pressure in the laminate resulting from a successive series of reflow cycles until the threshold T_c is reached. The calculation is based on *Equations* 3, *5* and 6.

It shows that the actual value of the decomposition temperature T_d is of little influence on N_d. The time-to-delamination values T288 and especially T260 determine N_d. Since the reference soldering profile has a peak temperature of 260°C it is clear why T260 is the parameter of primary importance for delamination. *Figure 2* gives N_d as a function of T260 and the T260/T288 ratio.

This analysis shows an important weakness in the IPC-4101 classification of the lead-free compatible laminates. The most critical parameter for delamination T260 is set to a minimum of 30 minutes for all lead-free /sheet-categories. *Figure 3* gives the TGA curve of a material that fulfils the high thermal performance boundary requirements of IPC-4101C: Td=340°C, T288=15min, T260=30min. This combination yields a minimal of only N_d=2 solder cycles-to-delamination versus N_d=7 for the other categories! The reason for this unwanted result is that a T260/T288=2 with a decomposition temperature Td=340°C allows for considerable decomposition at reflow temperature. Therefore we propose, *Ref. 4*, a set of adapted boundary conditions given in *Table 2* that will yield the desired result: an increasing number of solder cycles-to-delamination Nd with increasing thermal performance class characterised by a set of congruent TGA profiles. The N_d values of *Table 2* are consistent with the experimental work of Hövel and Verbrugge, *Ref. 5*.

This analysis is used as a basis for a PCB laminate specification guideline, *Ref. 4*, available at *www.edmp.be*.

Suggestions for laminate specification and standardisation

With a quantified decomposition reaction (k_0, E_a) and known resin content parameters (RC, *f*) the delamination behaviour of a PCB becomes predictable when the delamination threshold T_c is known. When laminates or pre-pregs are used which deviate in resin content from the tested laminate predictability can be retained. For this purpose either the datasheet should provide the model parameters k_0, E_a, T_c along with the resin content parameters (RC, *f*) of the tested laminate or provide material parameters from which these model parameters can be directly derived. A simple set of these parameters could be T_d (5%), T_d (2%), T288, resin content RC and filler loading of the resin *f*. Providing this set of parameters does not require additional testing effort, on the contrary. Td(2%) can directly be obtained from the same TGA measurement used to determine Td(5%) and is actually a requirement per IPC-TM-650, 2.4.24.6. The multiple time-to-delamination measurements T260, T288 and T300 can be replaced by a single relatively short T288 measurement. Providing RC and f for the TGA measurement is important since lowering the net resin content *(1-f)RC* will increase the decomposition temperature T_d and the time-to-delamination parameters. Unfortunately this requirement is missing today in IPC-4101C.

Applications and future work

The methodology is used and validated by us in the study of lead-free soldering compatibility of new low halogen laminates. The application of the method is also not limited to FR4 type laminates.

In *Ref. 4* the delamination model is combined with a via failure model to derive a quantitative overall PCB laminate selection methodology, see *Figure 4*. The via failure model is based on IPC-D-279, Appendix B. An improved via fatigue model based on finite-element modelling of the epoxy stress distribution is under development.

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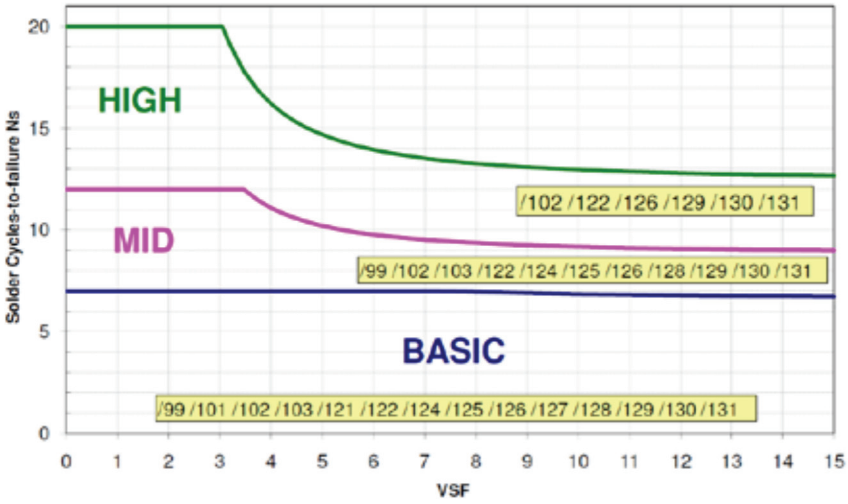

Figure 4. Solder cycles-to-failure for a combination of delamination and via failure based on the delamination model and the via failure model per IPC-D-279, Ref. 4.

Biography

Geert Willems is leading the Electronics Design & Manufacturing program (www.edmp.be) of imec (www.imec.be) and Sirris (www.sirris.be). The EDM program promotes scientific methodologies in PBA design, production and reliability. He combines a micro-electronics research background with a decade of PBA technology experience working for a telecommunication market leader where he had a leading position in preparing the transition to RoHS compliancy and lead-free assembly.

Piet Watté is a member of the PBA team of imec. He leads a Electronic Design & Manufacturing project aimed at developing Design-for-Manufacturing guidelines in collaboration with industry. He has a background as a physicist and material scientist. He is a 6-sigma black belt and has more than a decade of quality and reliability engineering experience at a leading electronics company.