Presented at IPC Printed Circuits Expo®
SMEMA Council APEX®
Designers Summit 04

Effect of Transient Thermal Profiles in Wave Soldering Processes on Connector Performance

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Abstract
Developing lead free connector products involves at least two distinct steps: removing the lead from the product and ensuring the product has sufficient thermal stability. Lead is most commonly found in terminal finishes and has been removed from most thermoplastic materials used in connectors. Ensuring sufficient thermal stability requires knowledge of the thermal excursions involved in soldering and how these excursions translate into product performance metrics.

For reflow soldering, we know the maximum soldering temperatures will increase by 20 to 30 °C. The magnitude of this change is not large, however, the temperature value, 260 °C, exceeds the melt point of many engineering thermoplastics. Since the cost of these plastics typically scales with melt temperature, an increase in thermal requirements can mean a significant cost increase.

In this paper we strive to understand the fundamental response of the plastics to the transient thermal excursions involved in wave soldering. FEM simulations demonstrate the thermal gradients that exist during these processes. These results can be used to understand the heat transfer and then to engineer the products to ensure reliability. Wave solder process simulation shows that the pin to plastic interface resides at a temperature very near to that of the solder. Connector terminals, made from copper based alloys, often have very high thermal diffusivities, increasing heat flow from the solder pot into the plastic. FEM results are compared to experimental results from lab and production manufactured testing of solderable interconnects. A test method for evaluating plastic performance in wave solder applications is proposed.

Introduction
Due to legislative pressures, customers are now requesting lead free products. As our customers migrate to lead free solder processes, the increased thermal demand may impact product performance. For reflow soldering, we know the maximum soldering temperatures will increase by 20 to 30 °C. The relative magnitude of this change is not large, however, the temperature value, 260 °C, exceeds the melt point of many engineering thermoplastics. Since the cost of these plastics typically scales with melt temperature, an increase in thermal requirements can mean a significant cost increase. While reflow temperatures can be daunting, the test methods used to predict plastic performance have already been proposed.[1, 2] The connector industry is following a modification of the IPC/JEDEC 020B test method to qualify products for lead free process compatibility in reflow.

Reflow soldering has been studied thoroughly in the literature, but the impact of higher temperature wave solder has received much less attention.[3] The thermal excursions in the plastic of a connector body are quite different in wave solder than they are in reflow solder. The primary source of heat is the result of heat transfer from the contact body to the metal to plastic interface. This leads to local thermal gradients, which can have locally high temperatures.

This report examines the transient thermal conditions that exist in a typical passive electronic component when subjected to wave soldering environments. These results are intended to help guide the development of a standard test method for qualification of passive components for lead free processing.

Background
The conversion to lead free manufacturing has generated the need for a number of new test methods. In this case, we are interested in resistance to soldering heat for connector products. While plenty of testing and performance monitoring has occurred in the past, there is no industry accepted[4] method of qualifying connector products for resistance to soldering heat in a Sn/Pb soldering environment. Thus, the process of developing a standard test method for lead free processing is complicated by the need to ensure that an analogous test method for Sn/Pb solder would have to be developed. The long history of performance of products soldered using Sn/Pb, provides excellent case history.

Engineering thermoplastic materials are ubiquitous in the connector industry. Low cost and injection moldable, these materials offer the mix of properties required for these applications. Two key properties relative to soldering performance are the heat deflection temperature and the melting point.[5, 6] These properties indicate the degree of softening that occurs during heating. This can also be quantified by the modulus, G', of the material. In a connector product, this relates to the ability of the connector to retain its shape, retard blister formation due to water absorption and retain contacts that have been mechanically inserted into plastic cavities.

During wave soldering, the sources of heat are from conduction, convection and radiation. The conductive portion is the most severe. In this case, heat from the solder bath conducts up the contact, typically a copper alloy with high thermal diffusivity, to the metal to plastic interface. Heat can conduct across the interface, the rate of which is primarily dependent upon the temperatures and the thermal diffusivity of the plastic materials. Since plastics have relatively low thermal diffusivity, they are not effective heat sinks and the temperature gradients at the metal to plastic interface are expected to be large.

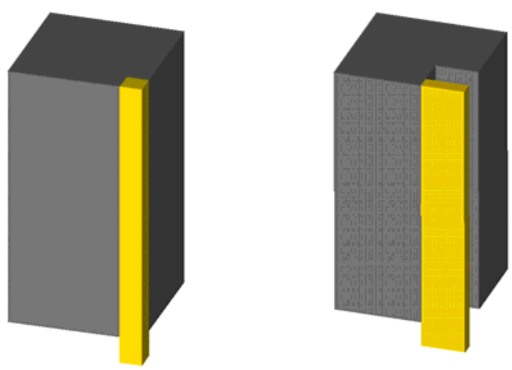
The second source of heat is the convection portion. This is heat transfer resulting from heated air above the solder bath or preheating conditions in the wave soldering process. This helps reduce thermal gradients in the component, but is a low temperature phenomenon compared to the melt temperatures and heat deflection temperatures of engineering thermoplastics. A printed circuit board (PCB) placed between the component and the solder bath effectively eliminates any convective heat transfer from the solder bath. Since the effect of convection heat transfer is small, it has been neglected in this study.

The third source of heat is from radiation heat transfer. Due to the low temperatures involved, radiation heat transfer is very small. Radiation heat transfer from the solder pot is eliminated when a PCB is used between the component and the solder bath. Thus, radiation heat transfer has been neglected in this study.

Simulation of wave soldering

To simulate the wave soldering process, a three-dimensional finite element model of the contact and plastic housing assembly was created. Because the model is quad-symmetric, one quarter of the assembly was used to simplify the analysis. Two geometrical variations of the assembly were created to represent two types of connector assembly processes. One, representing an insert molded or line-to-line fit 0.5mm x 0.5mm square contact in a hole of the same dimensions, is referred to as “overmolded.” The second, representing a staked 1.0mm x 0.33mm contact in a 1.0mm x 1.0mm hole, is referred to as “staked.” For both geometries, the contact extends beyond the plastic 0.3mm.

The plastic body housing was modeled as a 30% glass-filled PBT[7] and the contact was modeled as either C51100 phosphor bronze (CuSn4) or C19400 copper iron (CuFe2). The physical properties for these materials are shown in Table 1.



A B

Figure 1 - Quad Symmetric Geometry Used for FEM Analysis of Contacts Inserted in a Plastic Body. A) Overmolded Contact with Plastic to Metal Interfaces on Four Sides and B) Staked Contact with Plastic to Metal Interfaces on Parts of Two Sides

Table 1 - Physical Properties of Materials used in FEM Analysis

Property	**30% GF PBT**	**C51100**	**C19400**
Density (kg/m^3)	1530	8857	8913
Specific Heat (J/kgK)	1130	380	385
Melt Temperature (K)	498 (225 C)	~1356 (1083° C)	~1356 (1083 °C)
Latent Heat of Fusion (J/kg)	45000	n/a	n/a
Specific Heat at Melt (J/kgK)	1550	n/a	n/a
Thermal Conductivity (W/m K)	0.22	84	260
Elastic Modulus (Pa)	7.58×10^9	1.103×10^{11}	1.206×10^{11}
Poisson’s Ratio	0.3	0.3	0.3
Thermal Expansion (m/m K)	25.2×10^{-6}	17.5×10^{-6}	16.2×10^{-6}

To determine the resulting temperatures of the assembly while exposed to the wave solder process, a transient thermal analysis was performed using ANSYS.[8] The assembly was initially set to a uniform temperature of 297K (24 °C). To simulate the wave solder process, the surface of the contact located 0.3mm below the surface of the housing was set to a constant elevated temperature for a 5 second duration. The elevated temperatures used were 240 °C (513K) for simulating a typical Sn/Pb wave solder process and 265 °C (538K) for simulating a lead free process. Both contact materials were analyzed as well as both geometrical configurations. Effects due to preheating are expected to be small and were neglected.

For the initial analysis, the material properties were assumed to be linear and isotropic throughout the resulting temperature range. Thus, any phase change of the material (e.g., melting) was neglected.

The following thermal maps, Figures 2–5, show the resulting temperature variations of the assembly after 5 seconds of exposure to typical Sn/Pb wave solder conditions. Results are shown for both phosphor bronze and copper iron contacts and both the overmolded and staked conditions. The temperature used to simulate the Sn/Pb solder process is 513K (240 °C), which is above the melt temperature of the housing, 498K (225 °C). The simulation results for the overmolded condition indicate a maximum temperature in the plastic housing of 507K (234 C) and 512K (239 °C) for the phosphor bronze and copper iron contacts, respectively. Similarly, the simulation results for the staked condition indicate a maximum temperature in the plastic housing of 511K (238 °C) and 513K (240 °C) for the phosphor bronze and copper iron contacts, respectively.

As expected, due to its higher thermal conductivity, the copper iron contact and its surrounding area become hotter than the phosphor bronze contact and its surrounding area for both the overmolded and staked conditions. For all configurations, the applied temperature for the Sn/Pb wave solder process, and accordingly the maximum temperature in the assembly, is greater than the melt temperature of the plastic. Therefore, even in the existing Sn/Pb solder process, some melting of the plastic housing may occur.

The following thermal maps, Figures 6-9, show results for the same four configurations after a five-second exposure to typical lead free wave solder conditions. The temperature used for the lead free simulation is 538K (265 °C), which is above the 498K (225 °C) melt temperature of the plastic. For all four configurations, areas of the plastic housing reach the melt temperature. The orange areas shown on the thermal maps represent the areas that are at or above the melt temperature of the plastic, 498K (225 °C), after the five-second exposure.

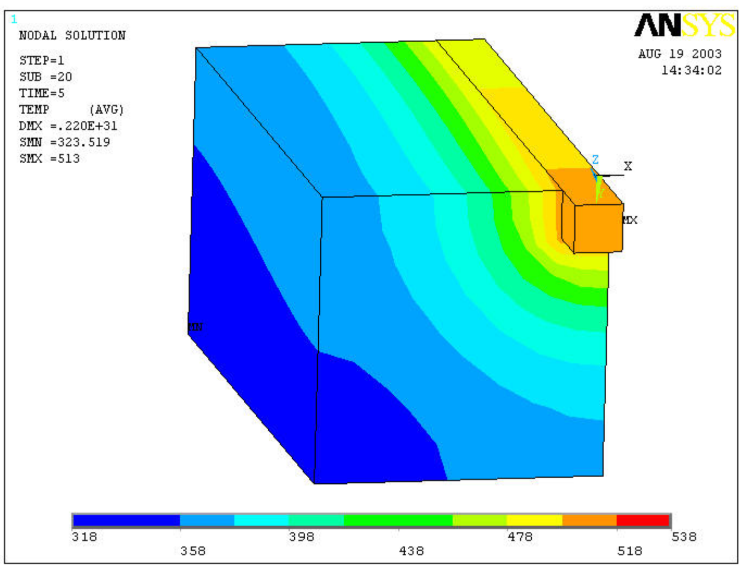


Figure 2 - Thermal Results of Simulated Overmolded, Phosphor Bronze Contacts, Exposed to Sn/Pb Wave Solder Conditions for 5 Seconds

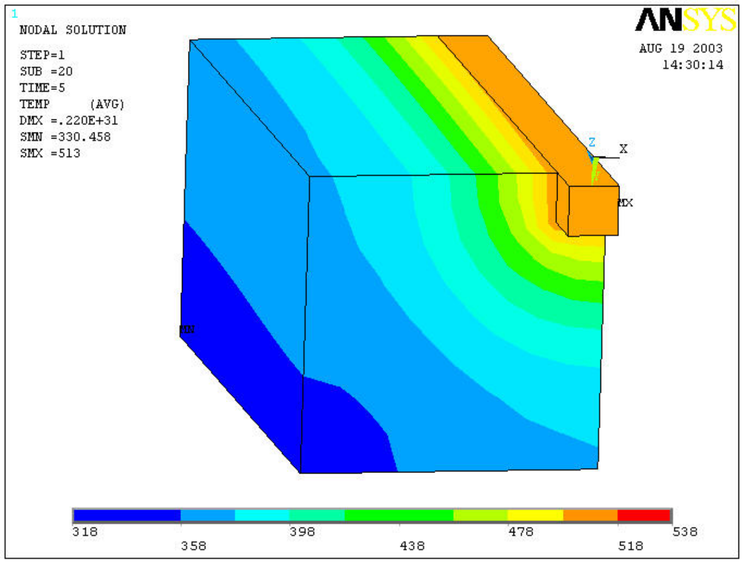


Figure 3 - Thermal Results of Simulated Overmolded, Copper Iron Contacts, Exposed to Sn/Pb Wave Solder ConditionsfFor 5 Seconds

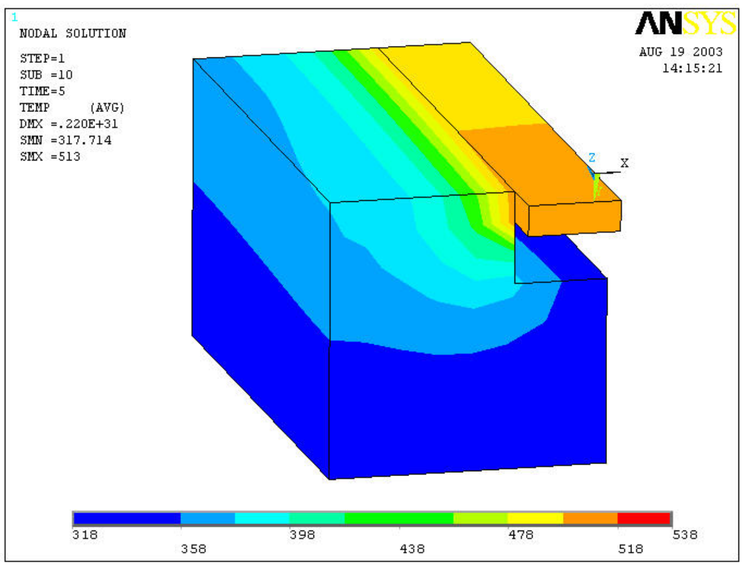


Figure 4 - Thermal Results of Simulated Staked, Phosphor Bronze Contacts, Exposed to Sn/Pb Wave Solder Conditions for 5 Seconds

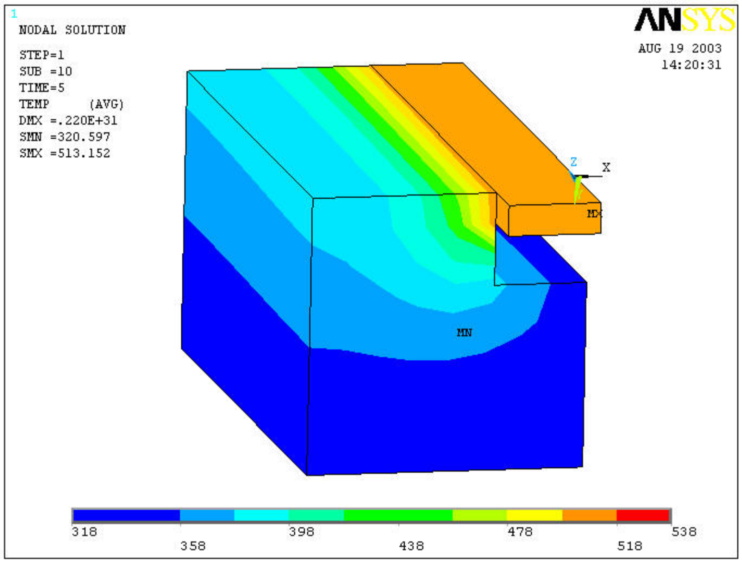


Figure 5 - Thermal Results of Simulated Staked, Copper Iron Contacts, Exposed to Sn/Pb Wave Solder Conditions for 5 Seconds

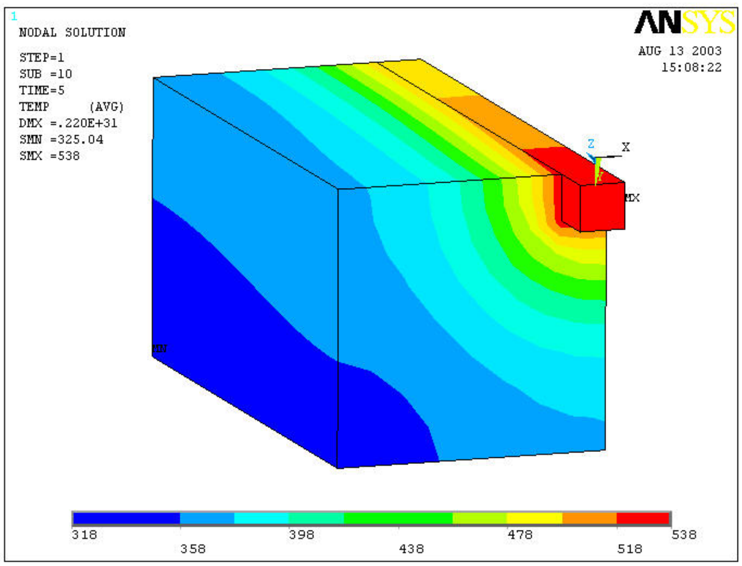


Figure 6 - Thermal Results of Simulated Overmolded, Phosphor Bronze Contacts, Exposed to Lead Free Wave Solder Conditions for 5 Seconds

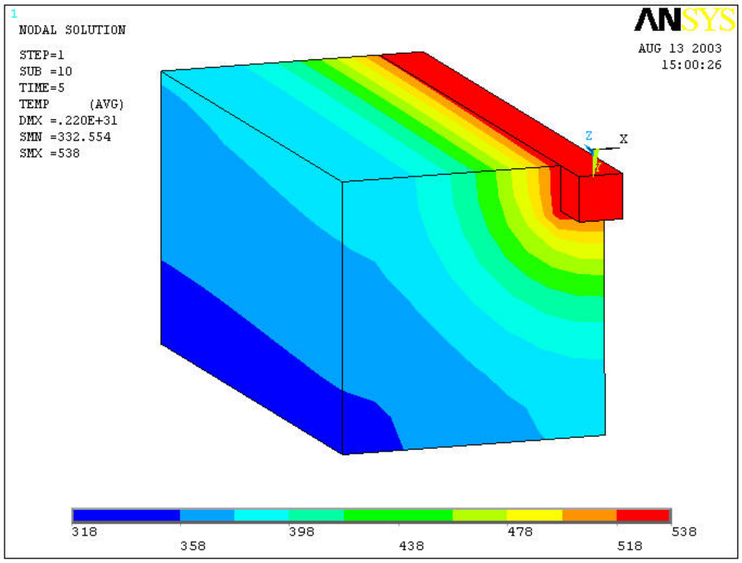


Figure 7 - Thermal Results of Simulated Overmolded, Copper Iron Contacts, Exposed to Lead Free Wave Solder Conditions for 5 Seconds

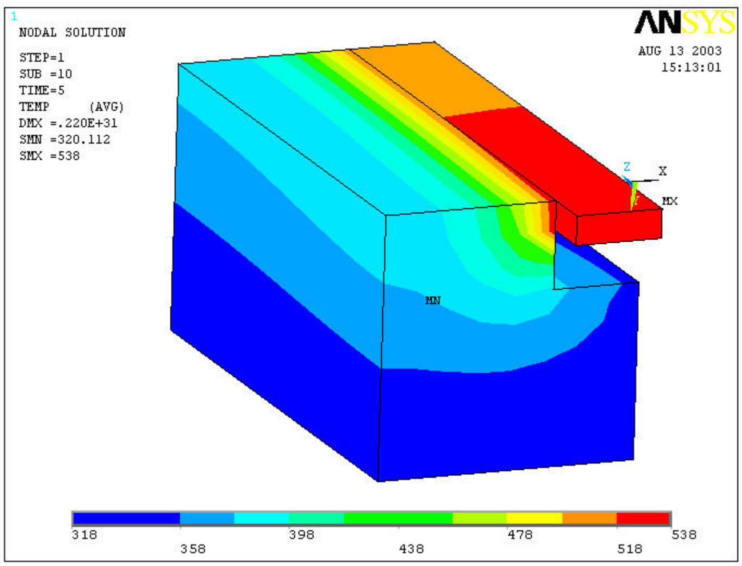


Figure 8 - Thermal Results of Simulated Staked, Phosphor Bronze Contacts, Exposed to Lead Free Wave Solder Conditions for 5 Seconds

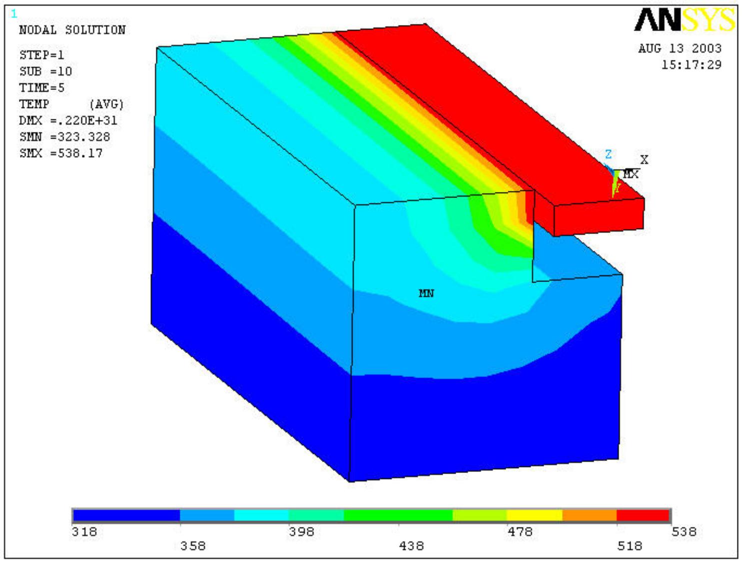


Figure 9 - Thermal Results of Simulated Staked, Copper Iron Contacts, Exposed To Lead Free Wave Solder Conditions for 5 Seconds

As before, the copper iron contact conducts more heat than the phosphor bronze contact and for the higher temperature lead free simulation, the entire copper iron contact and its immediate surrounding plastic area are at or above the melt temperature of the plastic after the five second exposure for both the overmolded and staked conditions.

The simulation results provided so far represent temperatures after 5 seconds of exposure. Since this is a variable parameter of wave soldering processes, it is useful to examine the progression of heat flow as a function of time. The following images, Figures 10-11, show the thermal progression at one-second increments. The entire copper iron contact reaches the melt temperature of the plastic in less than 2 seconds for the overmolded and staked conditions. The results depict the inherently high thermal diffusivity of these contacts.

In order to improve the accuracy of the model for temperature effects, the phase change of the material was taken into account by including the latent heat of fusion effect as the material changes from solid to liquid. This was done by defining an adjusted specific heat in the melt region equal to $L_f/\Delta T$, where L_f is the latent heat of fusion and ΔT is the temperature range of the melt region. The melt region does not have a definitive beginning and ending temperature; therefore, for modeling purposes, the temperature range was approximated by using a ΔT equal to 1K to represent the duration of the phase change from solid to liquid. The following chart and graphs show the defined values for specific heat at various temperatures and the resulting enthalpy values. The enthalpy is computed from the equation $H = \rho c \int dT$, where ρ is density, c is specific heat, and T is temperature.

Table 2 - Specific Heat and Enthalpy Values at Given Temperatures for PBT

Temp (°C)	Specific Heat (J/kg °C)	Enthalpy (J/m^3)
24	1130	5.13E+08
225	1130	8.61E+08
225.1	45000	8.68E+08
226	45000	9.30E+08
226.1	1300	9.30E+08
265	1300	9.97E+08

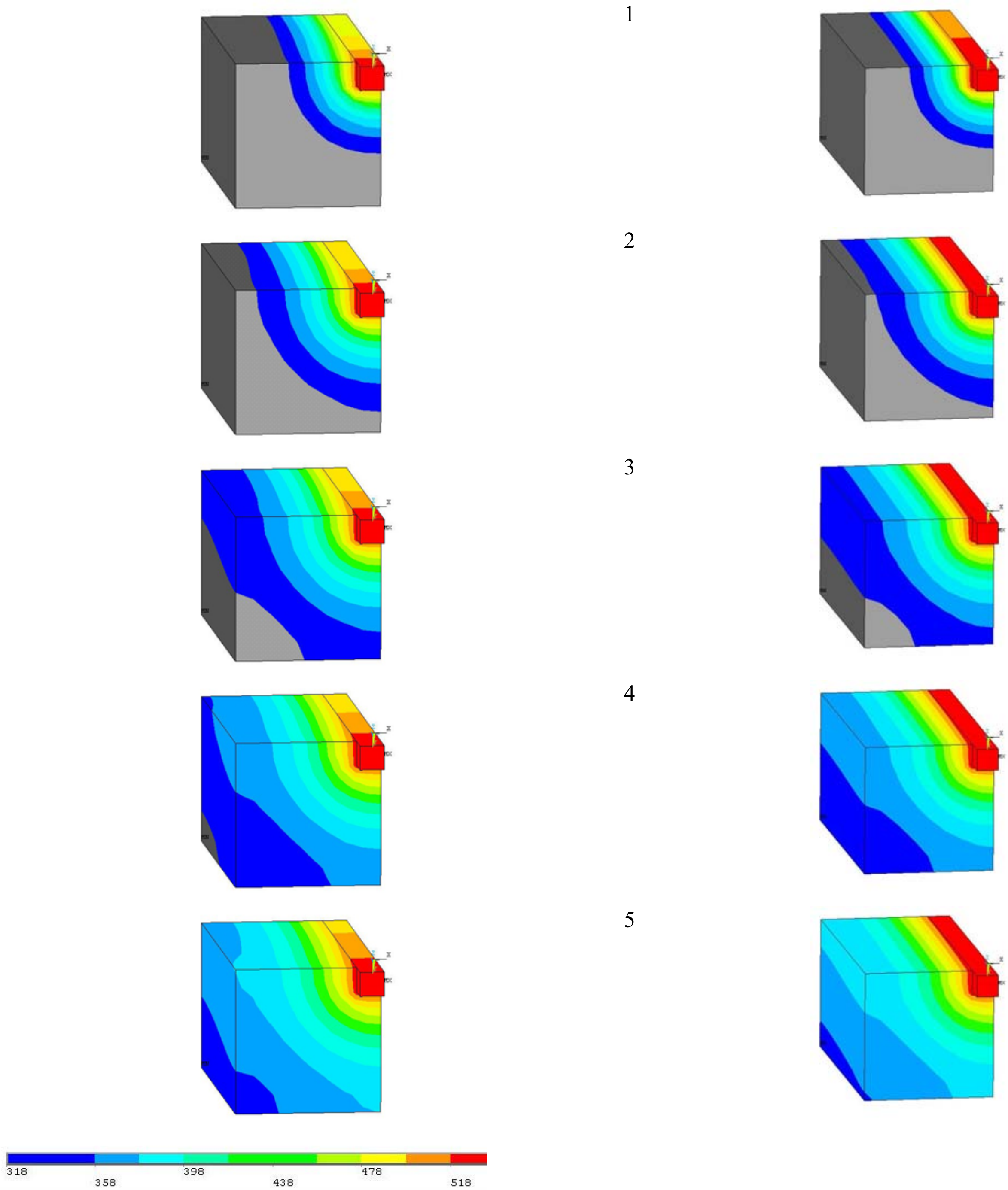


Figure 10 - Thermal Results Of Simulated Overmolded, Phosphor Bronze (Left) and Copper Iron (Right) Contacts, Exposed to Lead Free Wave Solder Conditions for 5 Seconds, Incorporating Phase Change Effects

Images show progression at one second increments from 1 to 5 seconds starting from the top. Orange areas indicate temperatures equal to or greater than the melt temperature of the plastic, 498K (225 °C), gray areas are less than 318K (45 °C).

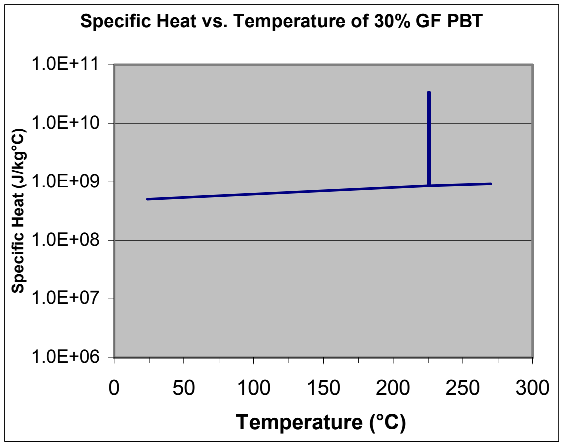


Figure 12 - Specific Heat vs. Temperature for 30% Glass-Filled PBT.

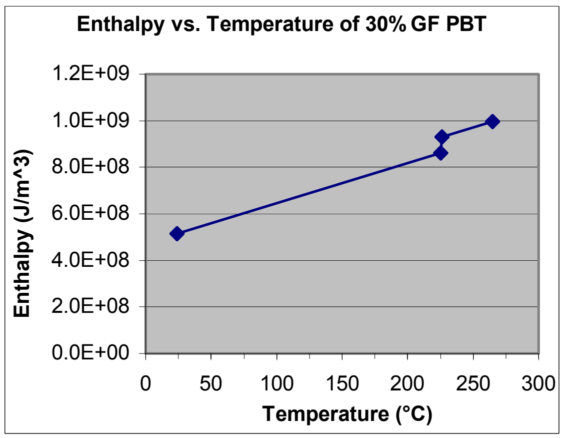


Figure 13 - Enthalpy vs. Temperature for 30% Glass-Filled PBT

To incorporate this into the ANSYS model, the specific heat was defined at the six temperatures shown in the table above. The melt temperature is represented by the range of temperatures at and between 225.1 and 226 °C (318.1 and 319K). As shown in Figures 14-17, the resulting effect is that the predicted overall temperature of the plastic housing is slightly lower; however, the volume of plastic that is exposed to the melt temperature is not significantly different than it was for the model that does not take into account the phase change of the plastic. The effect of the limited thermal diffusivity of the plastics is improved by the additional thermal lag due to the heat of fusion. The overall depth of penetration remains about the same since the energy contribution due to melting is small.

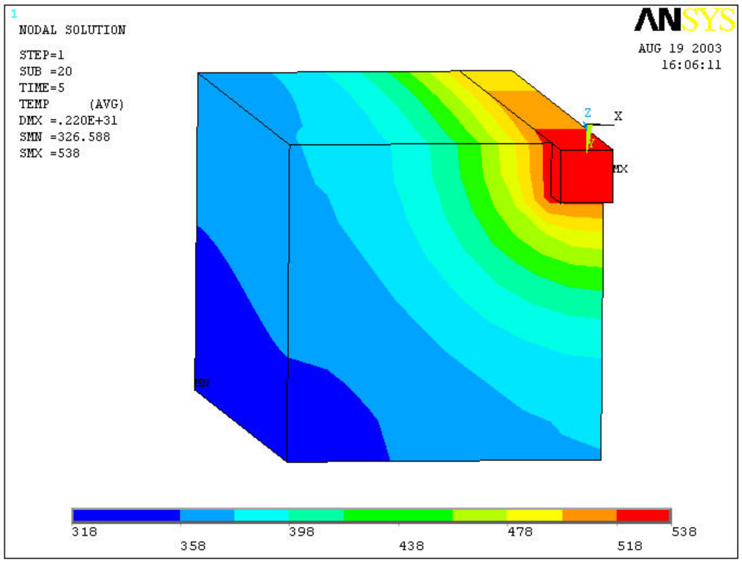


Figure 14 - Thermal Results of Simulated Overmolded, Phosphor Bronze Contacts, Exposed to Lead Free Wave Solder Conditions for 5 Seconds, Incorporating Phase Change Effects

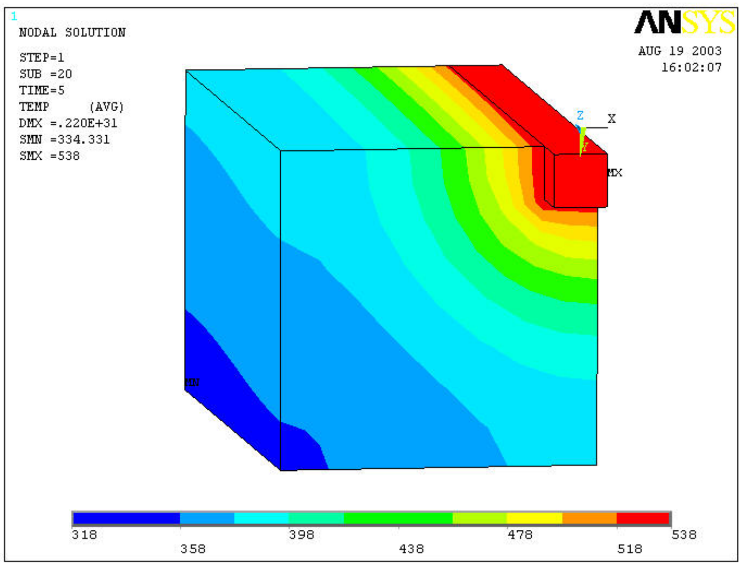


Figure 15 - Thermal Results of Simulated Overmolded, Copper Iron Contacts, Exposed to Lead Free Wave Solder Conditions for 5 Seconds, Incorporating Phase Change Effects

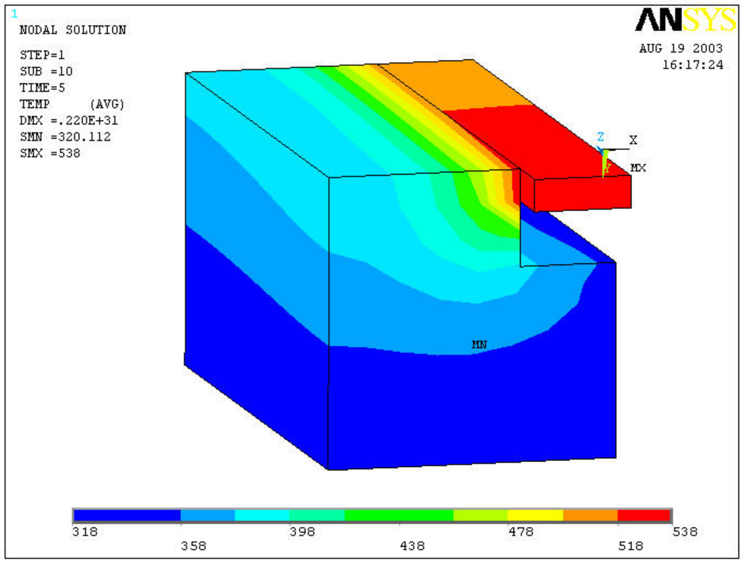


Figure 16 - Thermal Results of Simulated Staked, Phosphor Bronze Contacts, Exposed to Lead Free Wave Solder Conditions for 5 Seconds, Incorporating Phase Change Effects

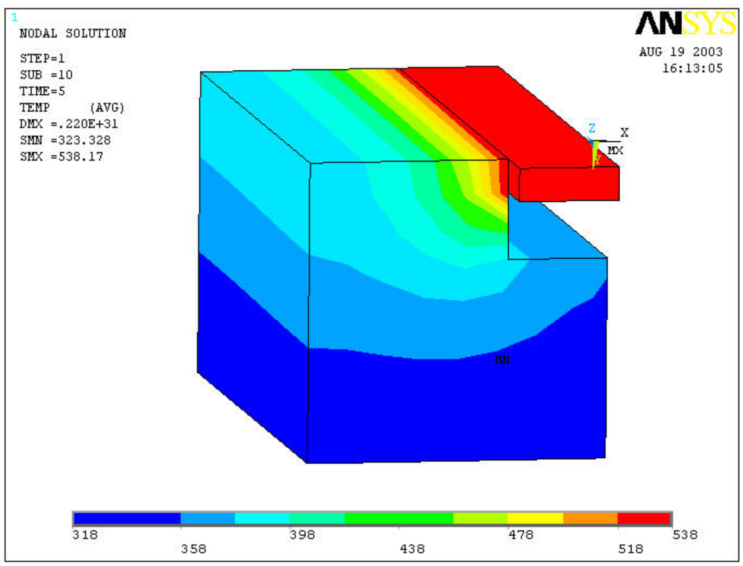


Figure 17 - Thermal Results of Simulated Staked, Copper Iron Contacts, Exposed to Lead Free Wave Solder Conditions for 5 Seconds, Incorporating Phase Change Effects

The maximum melt temperature penetration depth into the plastic, as shown in Figure 18, was calculated from the simulation results using a linear relationship to define the temperature between element nodes. The nodes along the outer edge of plastic closest to the applied heat were selected and the two nodes surrounding the melt temperature were determined. The distance between nodes is a user-defined parameter, so the change in temperature per unit length between these two nodes could easily be determined by subtracting their temperatures and dividing the result by the distance between nodes. Using this information, the distance from one node to the point where the temperature would be equal to the melt temperature was calculated. This distance was calculated for one-second intervals for both the phosphor bronze and copper iron contacts in the overmolded condition. These results are shown in Table 3.

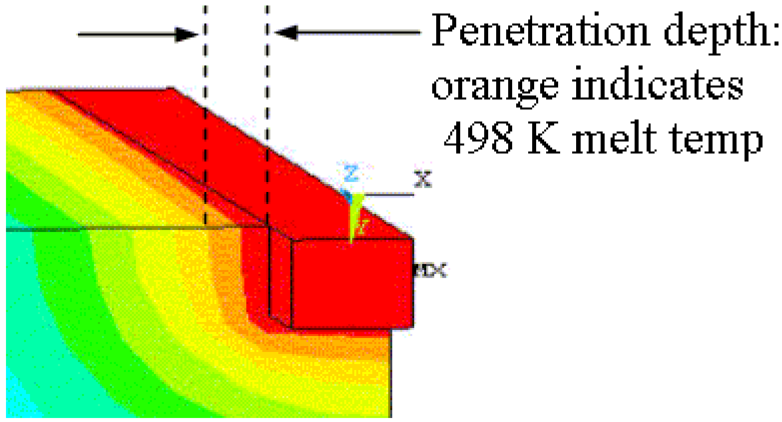


Figure 18 - Maximum Melt Temperature Penetration Depth into Plastic

Table 3 - Simulated Melt Temperature Maximum Penetration Depth into Plastic
Overmolded Condition - µm (mils).

Time (seconds)	Phosphor Bronze	Copper Iron
1	58 (2.3)	75 (3.0)
2	69 (2.7)	87 (3.4)
3	79 (3.1)	98 (3.8)
4	88 (3.5)	109 (4.3)
5	97 (3.8)	120 (4.7)

As may be expected, the response of the plastic housing material to transient thermal excursions is dependent on material selection, geometry and exposure time and temperature. In all combinations used for this simulation, some volume of the plastic housing reaches the applied temperature in less than one second. For this reason, it is critical to understand what the effects will be of a melted plastic region around the contact. Is the retention force affected and if so, how much? What penetration depth is acceptable and what is not? The answers to these questions will help determine the usability of various contact materials, what exposure time is acceptable, and which plastics can be used for lead free wave soldered products.

To investigate the effects that the heating may have on the retention force by way of plastic strain, another ANSYS simulation was performed. A structural model was generated from the same geometry used in the thermal analysis and the simulated wave solder temperatures after five seconds were used as input into the model. The following figure shows the resulting strain in the assembly when it is cooled from the melt point of the plastic, 225 °C, to ambient ,24 °C. The maximum strain value is 0.00277 mm/mm or 0.277%. This places the plastic in a state of elastic compressive stress that provides friction between the pin and plastic. Further, depending on the time above the melt, the plastic will have an opportunity to flow around the pin, providing some mechanical interlock to the surface of the pin. Thus, for overmolded products, little or no change in pin retention force is expected.

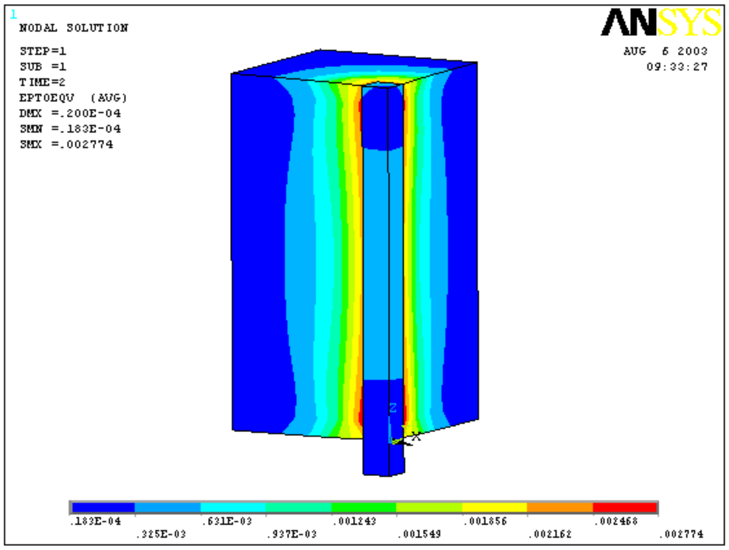


Figure 19 - Strain Map of Residual Strain Developed Around a Pin after Cooling from the Melt Point of the Polymer to Room Temperature

However, there are products with a similar geometry as the overmolded condition that are not overmolded. In those cases, the pin is inserted into a hole that is slightly smaller than the pin or is at worst case a line-to-line fit. This type of contact retention mechanism relies on the residual stress developed in the plastic housing to provide the normal force and friction required. During melting, this contact retention mechanism will lose the applied normal force as the plastic melts. During cooling, some normal force will develop, but it is lower than the normal force prior to soldering.

Proposed Test Method:

The test method we are currently using for lead free wave soldered products is a modification of the IEC 60068-2-20 specification. Connector products are fluxed with a rosin based flux, then dipped into a solder bath at 265 °C. The solder bath can be Sn/Pb or a lead free solder alloy. No printed circuit board is used as this represents the worst case scenario. No preheat of the component is provided in order to simplify the experiment. The product is dipped to an insertion depth that provides a gap of about 1 mm between the bottom of the plastic housing and the solder bath. The product is held in the solder bath for 10 seconds then removed. The product is inspected for each critical to function properties and their conformance to the engineering specifications. These properties include features such as:

- Contact retention
- Dimensions
- Flatness
- Indications of blistering or melting

This type of procedure can be used to qualify component families for lead free wave solder performance. When a product that has solder tails is used for pin-in-paste or intrusive reflow style soldering processes, this procedure should not be used. A procedure that mimics reflow soldering should be used.[9]

As an example of the test procedure, we tested three connector products used in the computer industry. The products were made with three materials, PBT, PPA and PCT. These products have melt temperatures of 225, 310 and 263 °C and heat deflection temperatures of 210, 277 and 261 °C respectively. The product had different contact retention mechanisms; the first two used an interference or overmold type of interface, while the PCT product used a lance feature to provide retention. Figure 20 below shows the contact retention force, which is a critical to function property for each of these products, at different times during the test. In each case, the result is the average of 12 tests. The first column is the force prior to testing. The next column is the force after testing at Sn/Pb solder temperatures, i.e., 240 °C. The last column is testing at lead free temperatures, 265 °C.

It is clear from the results that the performance of the retention feature is reduced after soldering exposure. Low temperature materials, like PBT, suffered a significant loss of retention force. High temperature materials, like PPA, also showed reduction in the retention force, though not as significant. The PCT product should have shown a significant reduction in retention force since the contact temperature should have exceeded the melt point of the plastic, 263 °C. However, this product uses a lance feature to provide contact retention. Thus, the plastic is not under stress except when the contact is being removed. Therefore as soon as the plastic re-solidifies, the contact retention returns to nearly the same level. These results indicate that the performance of a connector under wave solder conditions will be a function of both the plastic material selected and the product design features.

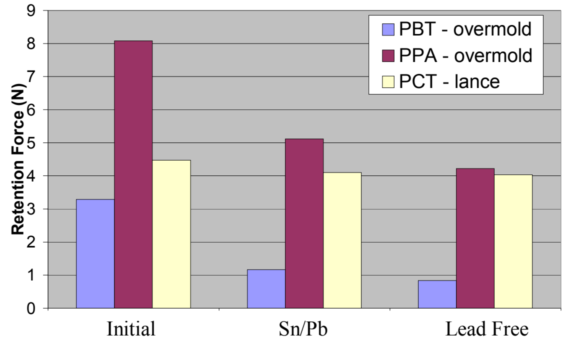


Figure 20 – Contact Retention Force of Contacts in Plastic Housings Initially and after Exposure to Sn/Pb and Lead Free Wave Solder Simulations

Conclusions

1) The primary source of heat in wave soldering is conduction through the contacts from the solder bath.
2) Copper alloys typically used in connectors will heat up to within a few degrees of the solder bath temperature in 1 second.
3) Thermal diffusivity of plastics are low so the depth of penetration of high heat into the plastic body is limited to about 120 microns.
4) Contact retention can be significantly affected by both Sn/Pb and lead free solder temperatures.
5) A test method for qualifying connectors to wave soldering has been proposed.

Acknowledgement

The authors would like to acknowledge the support of Marjorie Myers in providing wave solder simulation testing and Mike Walmsley for providing samples and retention force measurements.

References

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