CHALLENGES FOR SELECTING APPROPRIATE TIM2 MATERIAL FOR CPU

Priyanka Dobriyal, Sumit Soni, Chet Lee
Intel Corporation
Hillsboro, OR, USA
priyanka.dobriyal@intel.com

ABSTRACT
Current generation central processing units (CPUs) give off ever-increasing amounts of heat in a small and very concentrated area, which can be detrimental to CPU performance. To dissipate generated heat to the external environment, a heatsink with a thermal interface material (TIM2) is mounted on the CPU. However, finding a suitable TIM2 is not simple. Some of the parameters to benchmark TIM2 include thermal conductivity, thermal interface resistance, bond line thickness, conformity and viscosity. This paper presents a case study that focuses on evaluating the thermal performance of various TIM2 materials and other critical parameters which may need further improvement from supplier's side. This paper provides a methodology for selecting and qualifying a potential TIM2 material for various applications including automotive, servers, personal computers and internet of things.

Key words: heat sink (HS), CPU cooling TIM2 (thermal interface material between CPU and heatsink)

INTRODUCTION
Numerous advances made in the electronics industry are changing every aspect of human life. The ever-present demand for faster, thinner, lighter and more reliable electronics is usually met by more powerful CPUs. The operation of these powerful CPUs leads to heat buildup, which can cause electronics to degrade, shortening the product's lifespan. Therefore, heat management plays a major role in device performance. A heat sink is usually placed on top of a CPU (Figure 1) to act as a passive heat exchanger between the electronic device and a coolant fluid as shown in [1].

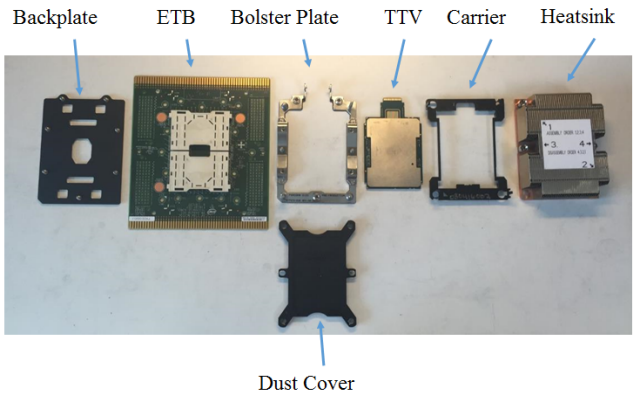

Figure 1. TIM2 applied on heat sink and assembly shown in package stack up.

Although the surfaces of heat sink and CPU appear smooth, microscopic non-uniformities make full contact between these two surfaces impossible. To aid heat conduction and reduce the interfacial thermal resistance, a thin layer of thermal interface material (TIM2) is sandwiched between the CPU and the heat sink, as illustrated in Figure 2 [2]. Hence, thermal management solutions such as thermal interface materials (TIMs) enable devices to stay cooler, perform better and last longer. High performance TIMs inserted between the CPU lid and heatsink provide a reworkable, low resistance thermal path in the package stack-up as shown in Figure 2.

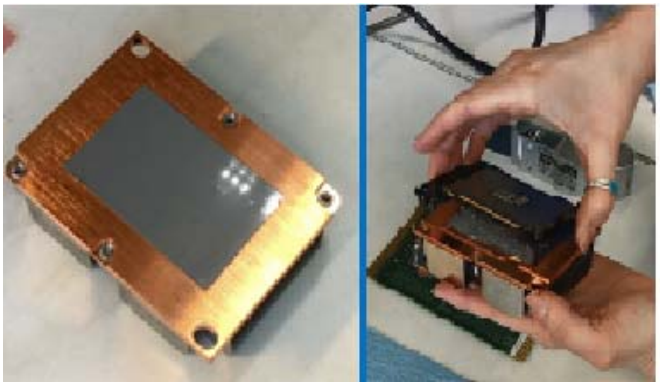

Figure 2. TIM2 applied on heat sink and assembly shown in package stack up.

Some of the parameters to benchmark TIM2 selection include heat transfer properties such as thermal conductivity

and thermal interface resistance, but also physical properties such as viscosity and conformity. There are several TIM2 materials available by suppliers, including ceramic- and metal-based pastes as well as polymer based material (PTIMs). A liquid or semi-liquid usually has good fluidity, and therefore such materials can coat the surface conformally. Pastes based on a liquid or semi-liquid carrier and containing additives of high thermal conductivity are described in numerous patents [3, 4, 5]. The most common carrier is silicone [6]. The disadvantages of silicone grease are messiness and difficulty of removal by solvent dissolution. Replacement of silicon grease with silicone rubber requires higher pressure and sometimes, even under high pressure, still has air gaps. This is mainly due to its higher viscosity and consequent less conformability. A better choice is a material which has ability to change phase upon change in temperature e.g. solid state at room temperature and liquid or semi-liquid state at the higher temperature. These are known as phase change materials (PCM).

A review of PCMs for use as latent heat materials was given by Lane [7]. Thermomechanical studies conducted with Differential Scanning Calorimetry (DSC), thermogravimetric analysis (TGA), etc. can provide useful insights to long-term reliability of TIM materials. For example, Yi et. al. performed differential scanning calorimetry (DSC) on several PCMs to determine which candidate would be most suitable for TIM application [8]. However, these findings were limited solely to material properties evaluation, rather than their performance in a CPU assembly (Figure 2). Another study by Yi et. al. was done to determine thermo-physical properties and curing behavior of a particular TIM2 used in microelectronic packaging [9]. However, when selecting a TIM for use in a particular product, information besides thermo-analytical data is required. The TIM may need to pass reliability testing before being applied to a CPU. It is necessary that a criteria from business unit is documented and tested upon receiving new TIM formulations from supplier prior application on real products. This paper provides an example of streamlined testing completed in selecting a TIM2 for a particular product. Studies include thermal conductivity measurements with aging, reliability over time (material degradation) and performance of TIM2 within a CPU's operating temperature range. At least five different commonly used TIM2 materials were selected for a Design of Experiment (DOE). Techniques such as DSC, thermal conductivity measurement as per ASTM D5470, qualitative analysis with the help of Fourier Transform Infrared Spectroscopy (FTIR), and Scanning Electron Microscopy/ Energy Dispersive X-Ray Spectroscopy (SEM/EDX) were performed to obtain desired results. Optical microscope (OM) was used to perform visual inspection. In addition, samples were aged and studies were repeated. The results can be extrapolated to understand what material properties suppliers should have in mind to formulate appropriate TIM2 materials.

EXPERIMENTAL

Materials

For this study 4 types of TIM2 materials were selected as shown in Table 1. Sample 1 and 2 served as a phase change material whereas sample 3 and 4 were traditional thermal grease. Thermal conductivity of all the four samples were measured as per D5470. Once thermal conductivity is measured, thermal impedance (resistance) and volumetric resistivity can be calculated with a known spread area and TIM thickness. These specimens were then aged using accelerated stress testing (Shock, Vibration and Bake). Thermal performance data was collected for before and after comparison.

Table 1. Sample Details as-received

TIM2 Material	Type	Thermal Conductivity (W/m.K)	Thickness, L (m)	Cross Section Area, A (m2)	Thermal Resistance (K.m2/W)	Volumetric Resistivity
Sample 1	Phase Change Material 1	2.5	0.00025	0.00329	0.0001	0.001316
Sample 2	Phase Change Material 2	2.3	0.00025	0.00329	0.0001087	0.0014304
Sample 3	Thermal Grease 1	3.5	0.00025	0.00329	0.0000714	0.00094
Sample 4	Thermal Grease 2	3.6	0.00025	0.00329	0.0000694	0.0009139

Analytical techniques

To study TIM2 morphologies before and after aging, OM and SEM were performed. EDX performed on as-received TIM materials provided insights to their chemical (inorganic) nature. To age, samples were subjected for accelerated stress testing. FTIR was done to get the details on the chemical nature of TIM2 (organic and inorganic). For DSC, TA modulated Differential Scanning Calorimeter Non-isothermal DSC experiments were performed at a heating rate of 10 °C/min from 25 to 300 °C. For each experimental condition the measurement was repeated at least three times.

Thermal Conductivity Measurements (TCM)

TCM were done as per ASTM D5470 (Figure 3). This standard covers a test method for measurement of thermal impedance and calculation of an apparent thermal conductivity for thermally conductive electrical insulation materials ranging from liquid compounds to hard solid materials.

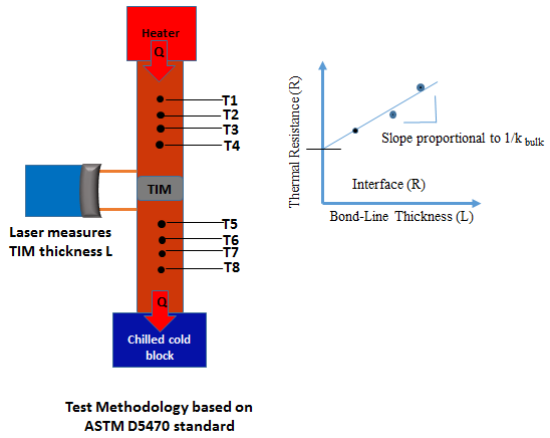

Figure 3. Thermal conductivity measurement set up.

Accelerated Stress Testing

In order to perform shock testing TIM2 materials were applied and assembled in the heat sink assembly. The amount of TIM2 material was optimized for this application. Once assembled these assembled heat sinks were further mounted over an electrical test board to simulate the actual use conditions. After this complete assembly specimens were mounted on a Shock Table (Lansmont 95/115D) using an aluminum fixture and standoffs (Figure 4). The mounted assembly was subject to Intel's board level shock test conditions. These test conditions corresponds to drops during shipping. Three drops in each of six orientation (+/- X, +/- Y, +/- Z) were applied to this assembly. Samples were characterized before and after shock testing for thermal performance (wind tunnel test) and materials analysis (SEM, FTIR, and DSC).

Figure 4. Mechanical shock test setup.

A similar setup was used for the mechanical vibration testing (Figure 5). A random vibration profile using Intel's test conditions was applied. After vibration testing, samples were tested for thermal performance and material analysis was performed.

Figure 5. Mechanical Vibration test setup.

All four sample assemblies (one for each TIM2 material used in this study) were isothermally baked in a thermal oven for five years of field life. Arrhenius type of modeling was employed for this accelerated bake testing (Eq. 1). In Eq. 1 k is Boltzman's constant and T_1 (use condition temperature) < T_2 (accelerated temperature) in Kelvin.

$$AF = e^{\frac{-Q}{k}\left[\frac{1}{T1}-\frac{1}{T2}\right]} \quad \text{Eq. 1}$$

Once the acceleration factor (AF) is calculated, the duration for accelerated bake testing can be calculated using Eq. 2.

$$t_{stress} = AF.t_{use} \quad \text{Eq. 2}$$

Thermal Performance Testing

Thermal performance measurements on CPU thermal test vehicles (TTVs) were performed in a wind tunnel (Figure 6) utilizing the appropriate loading mechanism and heat sink. First, air was introduced to simulate the air-flow seen in a server chassis. Next, the TTV embedded heaters were powered up to represent the die power of the processor. Air entering the wind tunnel was maintained at room temperature. Air was not preheated as the specified CPU maximum local ambient temperature was to be represented. Finally, a temperature correction factor was added to the results in order to account for the ambient temperature difference. This is important to include because the processor case temperature is not at the maximum allowed by specification. Instead it was closer to 40-50°C depending on the cooling solution and airflow.

Figure 6. Wind tunnel test set up.

RESULTS AND DISCUSSION

Various material analysis techniques were used to qualitatively analyze the chemical compositions of TIM2 samples. From EDX, Samples 1 and 2 were found to have very similar inorganic compositions, as shown in Figure 7.

Both material contain Aluminum (Al) particles in organic polymer matrices.

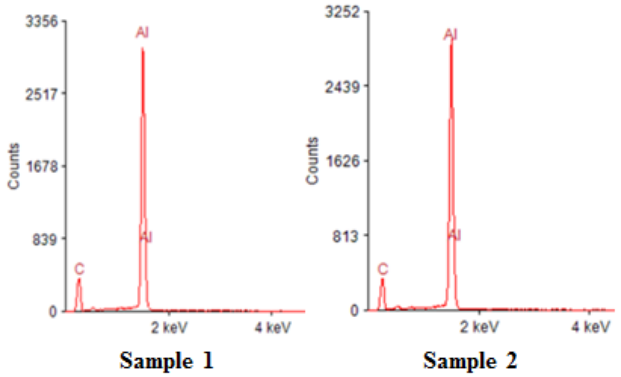

Figure 7. EDX analysis of TIM2 material samples 1 and 2.

In samples 3 and 4, EDX analysis detected Silicon (Si) and Sodium (Na) in addition to Al particles; therefore, samples 3 and 4 have different chemical compositions than samples 1 and 2. Thermal greases may have sodium silicate which offers higher thermal contact conductance. Organic content, as determined by carbon and oxygen EDX peaks, in sample 3 was significantly lower than sample 4 (Figure 8). Samples 1 and 2 were PCMs, whereas samples 3 and 4 were thermal greases; hence these EDX results were expected. Polymer-based TIMs usually have ceramic materials such as aluminum oxides (Al_2O_3), Boron nitride (BN) dispersed in the matrix of polymer (PCM in this case). Thermal greases, on the other hand, are typically a silicone-based matrix loaded with particles (such as AlN or ZnO) to enhance thermal conductivity. However these are susceptible to grease pump-out and material separation.

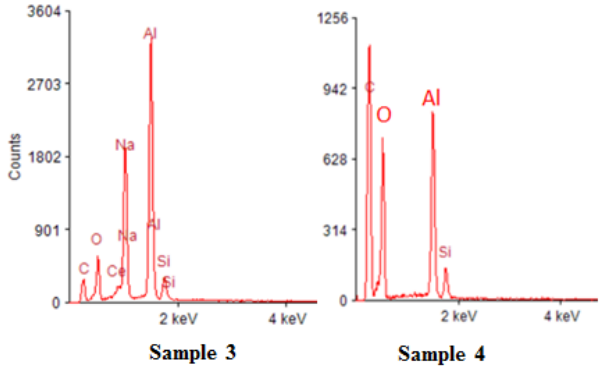

Figure 8. EDX analysis of sample 3 and 4 TIM2 material.

Structurally, phase change material has longer polymer chains and more consistent filler material (Al). This morphology helps minimize the filler migration which is essential for optimum TIM performance. In case of thermal greases, polymer chain length may be smaller and less rigid which provides good flow performance. However, this could also result in filler migration, agglomeration or drying out of the material. All these issues can cause performance and reliability issues. Figure 9 shows the morphology of phase change material vs thermal grease.

Higher viscosity in PCM leads to increased stability and hence less susceptibility to pump-out and in turn delamination. On the negative side, PCM tends to have lower thermal conductivities and higher surface resistances than grease. Even though thermal greases have better thermal conductivity at time zero, they still have higher degradation rates than PCM formulations.

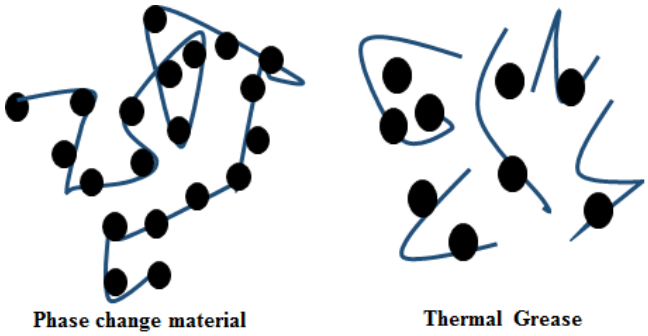

Figure 9. Morphological differences between the phase change vs thermal grease TIM2.

The higher degradation rates of thermal greases are due to their lower mechanical surface adhesion resulting in air pockets between the CPU and heatsink surfaces. PCMs fix this problem by completely wetting the CPU-HS surface during their phase change state. At phase transition temperature, PCMs allow polymer chains to melt and fill the air gaps. Therefore, even though a PCM material has lower thermal conductivity at time zero, it still provides improved thermal performance as compared to thermal grease.

Accelerated stress tests have been used for years to assess TIM2 performance over time. Mechanical Shock and Vibration stress testing are among the most widely used test methods to assess reliability risks during shipping and handling. Such stress testing is critical since TIM2 material can significantly degrade during shock and vibrations. Therefore, conducting such measurements as a part of TIM2 selection procedure is essential. After the stress testing, samples were tested for thermal performances using wind tunnel set up. This allowed comparison between before and after stress (Table 2). As noted in Table 2, the percentage change in thermal resistance showed minimal changes post shock and vibration.

Table 2. Percentage change in thermal resistance of all four TIM2 materials.

	% Change in Thermal Resistance		
Sample	**Post Shock**	**Post Vibe**	**Post Bake**
1	**1.0**	**0.0**	**1.5**
2	**6.6**	**0.8**	**17.3**
3	**0.4**	**2.0**	**4.5**
4	**0.0**	**0.0**	**5.5**

Following thermal performance testing, samples were disassembled and samples were inspected to see the stress impact on TIM conformity. Images are shown in Figure 10. Sample 3 which was thermal grease had valleys and rivers as a result of grease pump out and hence it is not optimum for a TIM2 from application aspect. This could worsen the thermal performance over time. Sample 4 visually looked best as it maintained integrity post stress testing even when compared to samples 1 and 2 which showed cracks and peeled off from the HS surface.

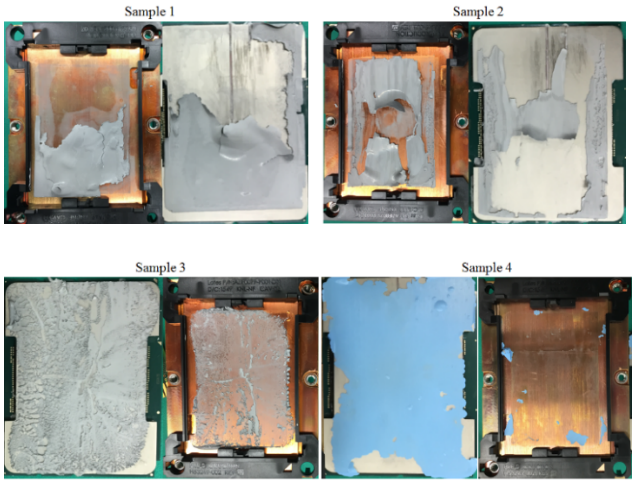

Figure 10. Visual inspection of TIM2 material post stress testing to look for air gaps and defects.

SEM images shown in Figure 11 were analyzed to see the change in material properties post stress. No general change was seen in comparing images collected at similar magnification (100X).

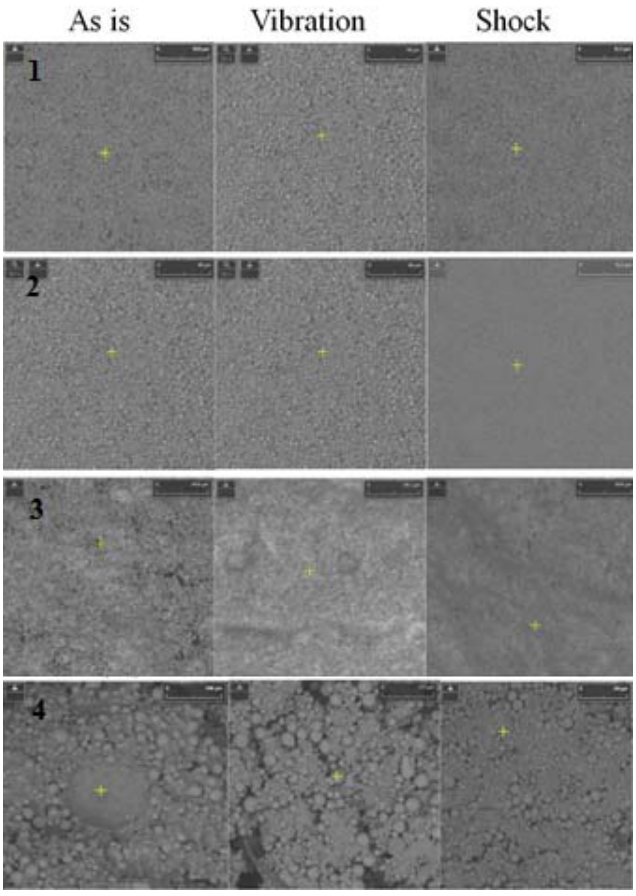

Figure 11. SEM imaging of all TIM2 material post shock and vibration compared with as-received TIM material. The magnification as 100X for all the images.

An additional way to qualitatively observe the changes in the material properties is through organic FTIR analysis (Figure 12). FTIR analysis on the TIM materials showed typical Alkyl C-H stretch observed at 2950–2850 cm^{-1} associated with polymer matrix on all the samples. The infrared absorption spectra of organosilicon compounds are very distinctive. Sample 4 which as per the EDX data contained Si and is a grease by nature showed typical peaks associated with Si-H deformation occurring in the 900-800 cm^{-1} region. Si organic compounds with a methyl group attached to the Si atom are very common giving rise to a characteristic sharp symmetrical deformation absorption around 1260 cm^{-1}. The asymmetrical deformation is weaker and occurs around 1400 cm^{-1}. Samples 3 and 4 were both greases but organic composition was found to be quite different. The organic composition of samples 1 and 2 was almost identical. The molecular weight of the polymer (chain length) may be different and hence they had some dissimilarities seen under FTIR. Post stress all the samples were analyzed by FTIR again and compared with as-received material in order to the effect of stress on the polymer backbone integrity. As expected, no changes were seen post shock and vibration as expected.

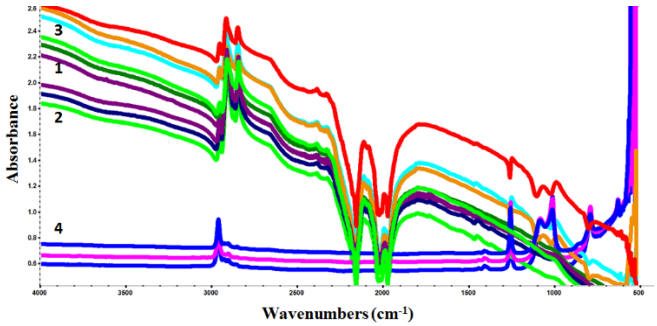

Figure 12. FTIR analysis of all four TIM2 Material (as-received vs post shock and vibration) to study impact on morphology post stress.

Thermo-physical properties of the samples were studied using DSC technique. Since organic and inorganic nature of samples 1 and 2 were identical, only sample 2 was selected for DSC to compare with sample 3. The normal operating range for a CPU is 50-100 ^{0}C and hence this range was closely observed for any transitions which could affect TIM performance. DSC can provide an insight to thermal cycling instability of the material evident by the peaks (endothermic/exothermic) observed in the temperature range of interest. DSC on PCM (sample 2) showed an endothermic peak at ~50 ^{0}C which is the phase change temperature of the material itself (Figure 13). Phase change is a one time, physical process which occurs to provide the fluidity to the PCM. No other transitions were seen between 50-100 ^{0}C which makes sample 2 a good candidate for TIM2. The degradation peaks occurring >200 ^{0}C are far beyond the operating range and remained unchanged when compared with the DSC of an aged sample.

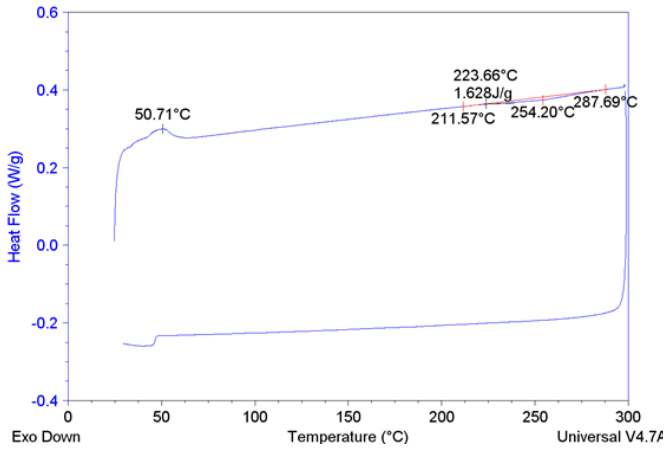

Figure 13. DSC isothermal evaluation Sample 2.

Sample 3 which was a thermal grease showed the degradation onset from ~222 ^{0}C. The endothermic peak was seen at ~266 ^{0}C. The amount of heat released in this transition was 13.5 J/g. There was another endothermic peak seen at 130 ^{0}C which could be a result of pump out (Figure 14).

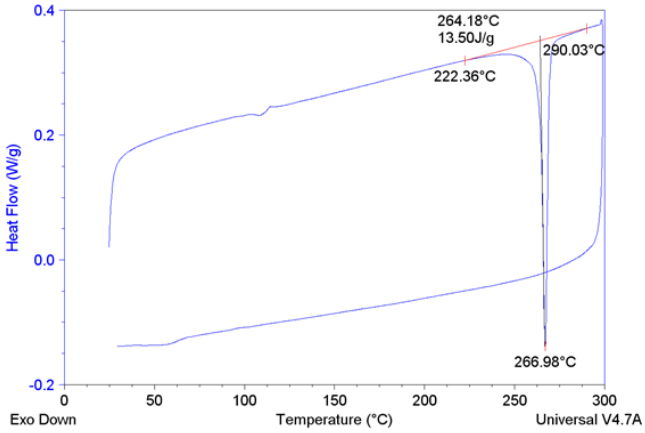

Figure 14. DSC isothermal evaluation Sample 3.

In this study, baking showed the most degradation in the thermal performance for all 4 samples (Table 2). In order to understand such degradation, post-bake samples were analyzed with the help of SEM and FTIR. Figure 15 shows the SEM image comparison done on sample 1 pre- and post-bake. The pre-baked sample seemed to be flexible with continuous organic phase and uniformly distributed Al particles. However post-bake sample 1 seemed to have tightly packed filler material with lesser indication of an organic phase (Figure 15, 17). This is because of the degradation of the polymer matrix and agglomeration of filler particles post-bake.

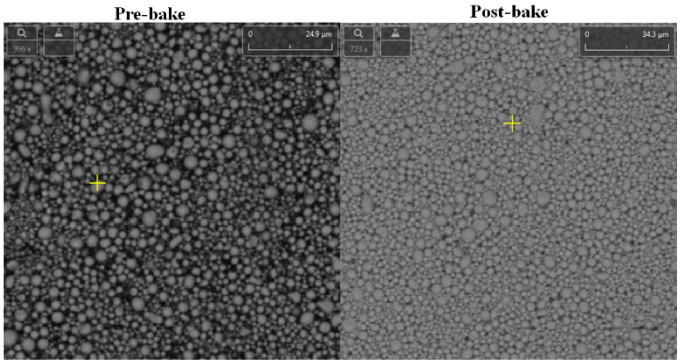

Figure 15. SEM images of Pre and Post bake sample 1. Annealed for 5 years of field life. Images were taken at 1000X.

This was further confirmed with the help of FTIR shown in Figure 16. The degradation of the polymer matrix was evident from the big drop of C-H absorbance seen in the FTIR spectra of post bake sample as compared to pre baking. The peak that emerged in sample post baking between 2300 cm^{-}1 and 2400 cm^{-}1 is associated with a O=C=O bonding stretch as a result of oxidation of the polymer. A broad peak between 3200 cm^{1}-3500 cm^{-}1 is due to intermolecular O-H bonds which resulted due to cross linking and hence showed up post-baking. All these peaks confirm the degradation of polymer backbone which would

result in the filler particles coming close together to agglomerate as seen in SEM imaging as well.

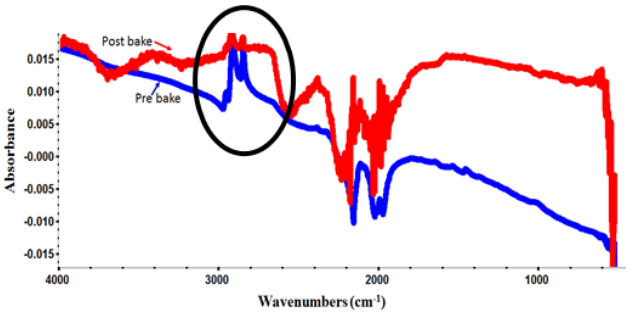

Figure 16. FTIR analysis on pre and post bake sample 1.

This agglomeration provides rationale for the thermal resistance increase post-bake in PCMs (Table 2). During isothermal bake, organic polymer degrades (see Figure 16) and we observe C-H peak disappearing in the FTIR spectra. This allows creation of extra air pockets between CPU and heatsink resulting into a higher thermal resistance. We also observed grain growth as a result of isothermal bake (Figure 17).

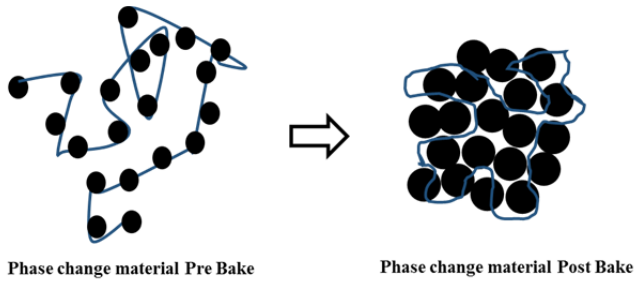

Figure 17. Sketch showing aggregation of Al particles as a result of isothermal bake for PCM material.

CONCLUSIONS

A streamlined method of TIM2 qualification aligned with product needs was documented in this paper. Materials were analyzed as-received as well as post aging. The results hence include the performance of a TIM2 material after number of years on field. Performance of TIM2 post reliability testing further provided data which extrapolates to number of years on field. Qualitative analysis by visual inspection looking for air gaps, FTIR for organic characterizations post aging vs. as-received determined changes post reliability tests. Thermal performance, chemical nature and morphologies didn't show any effect post shock and vibration. However, post baking differences were seen and documented. Thermo-mechanical studies were performed keeping CPU operating range in mind making sure that those do not affect the TIM2 performances. These results give a fairly straight forward decision making criteria for TIM2 selection.

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