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Arlon Silicones Technology

Thermal-Mechanical Decoupling by a Thermal Interface Material

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Abstract

Thermal-mechanical decoupling by a silicone thermal interface material (TIM) is one of the most important properties in electronic applications involving a printed circuit board (PCB). Thermal-mechanical decoupling requires that the thermal interface material have low shear modulus and high elongation, while maintaining the integrity of other properties such as shear strength and thermal conductivity. The shear modulus and elongation of a thermal interface material depend on the structure of the material, which dictates the mechanical and thermal properties. The effect of crosslink density, molecular weight, the reinforcing filler system, the extending filler system, and the Payne effect on shear modulus and other mechanical properties are investigated in detail below. An analysis of the thermal-mechanical decoupling mechanism is included, as well as an introduction to viable approaches to lower the shear modulus of a silicone Thermal Interface Material.

Contents

I. Introduction

Thermal interface materials (TIM's), such as Arlon's Thermabond® silicone adhesive, are used for bonding a printed circuit board (PCB) to a heat sink (usually aluminum), which dissipates heat away from the PCB. Silicone is primarily chosen as the adhesive polymer matrix because of its excellent thermal stability, low shear modulus, and good elasticity. The silicone TIM provides the following functions: 1) Bonding -- Bonding is particularly critical in vibration environments, such as automotive and aerospace. 2) Thermal-mechanical decoupling -- The PCB and aluminum heat sink have different Coefficients of

Thermal Expansion (CTE). During thermal cycling, the PCB and the aluminum expand and contract at different rates and different amounts. The CTE mismatch produces stress on the PCB driven by the aluminum sink, leading to possible PCB damage. The TIM, however, has a much lower shear modulus than the PCB or the aluminum. The compliance of the adhesive permits the decoupling of thermal expansion and contraction. 3) Dissipating thermal energy -- Conductive fillers in the TIM provide a heat transfer path to the aluminum heat sink. 4) Insulating electrically -- The TIM must provide dielectric breakdown protection and leakage current protection in the electronic application. The TIM can be made electrically conductive if a ground plane from the PCB to the Heat Sink is required.

II. Mechanism of thermal-mechanical decoupling

The shear modulus of the TIM is the most important aspect of thermal-mechanical decoupling. The thermal expansion and contraction of the PCB and the heat sink is shown in Figure 1. During a system's life cycle, the respective temperatures of the PCB and the heat sink will increase and decrease. In this thermal cycle, the PCB and the heat sink both deform but at different rates due to their various CTE's. Therefore, because the moduli of the PCB and the heat sink are much higher than that of the TIM between them, the thermal expansion and/or contraction amounts of the PCB and the heat sink are not dependent on the TIM, but, rather, solely on their respective CTE and

temperature differences. However, the induced stress of the PCB and the heat sink do depend on the modulus of the decoupling material. At the same deformation amount, a high shear modulus decoupling material such as an epoxy TIM induces more stress than does a low shear modulus TIM such as Arlon Thermabond® adhesive. If the stress is too high, it can deform and eventually damage the PCB (See Figure 2 below).

The mechanical properties of the TIM including shear modulus are determined by the structure of the material. The structure includes the chemical make up of the matrix, molecular weight, crosslink density, filler -- reinforcing and extending, and the interaction between the matrix and filler systems.
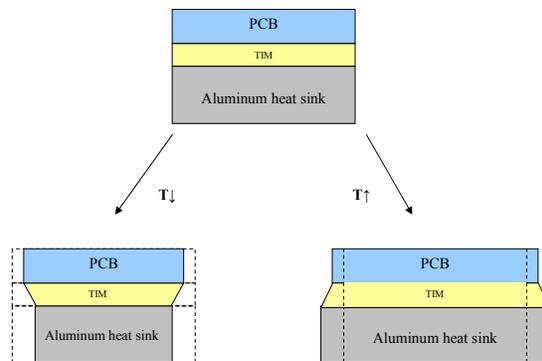

Figure 1: Thermal Expansion or Contraction of a PCB & Heat Sink during Thermal Cycling
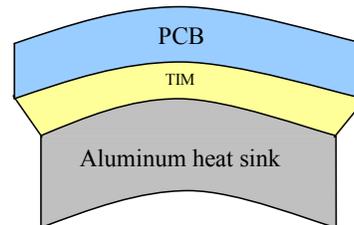

Figure 2: The Deformation of a PCB Due to Stress

III. The effect of crosslink density

The polymer chains of silicone rubber are entangled, but they can be steadily disentangled under stress, leading to a viscous flow. The deformation can be partially recovered and the strength is low. Cross-linking or vulcanization is the process in which the polymer chains are linked together chemically by short chemical bonds to form a network, therefore transforming the material from a viscous material to an elastic solid. The cross-linking points restrict the disentanglement and deformation can be recovered and strength is high.
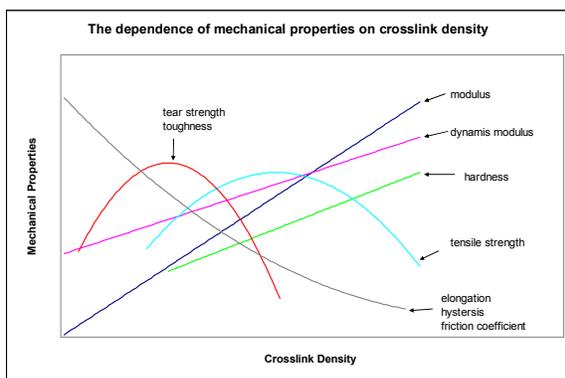
Figure 3: The Dependence of Mechanical Properties on Crosslink Density[1]

The mechanical properties of silicone rubber are greatly dependent on crosslink density, as is shown schematically in Figure 3. The shear modulus and hardness increase monotonically as the crosslink density increases; the material becomes more elastic or less hysteretic and the tensile strength passes through a maximum[1].

IV. The effect of the molecular weight of silicone rubber [3]

The length of the polymer chain increases with molecular weight. Physical entanglement increases with the length of the polymer chain. The strength and shear modulus increase with the entanglement of the polymer chain. Therefore, the strength and shear modulus of cured silicone rubber increase as the molecular weight increases.

V. The effect of the reinforcing filler system

For the majority of applications, silicone rubber is too weak to use without reinforcing filler. Almost from the debut of the silicone industry, fumed silica and precipitated silica have been used as reinforcing fillers in silicone. Fumed silica has different properties and manufacturing processes than precipitated silica, and is more often utilized because of its high purity and low silanol-group density. The primary particles of fumed silica are extremely small spheres of only a few nanometers. Dispersion of fumed silica in the siloxane matrix is important for technical applications, particularly when good mechanical properties are required, due to filler networking. Good dispersion leads to improved reinforcement and subsequently excellent silicone physical properties.

A. Filler content

The mechanical properties of silicone rubber are also greatly dependent on the reinforcing filler content (see Figure 4 below). The shear modulus and hardness

increase monotonically with increasing reinforcing filler content. The tensile strength passes through a maximum and the elongation decreases monotonically with filler content.
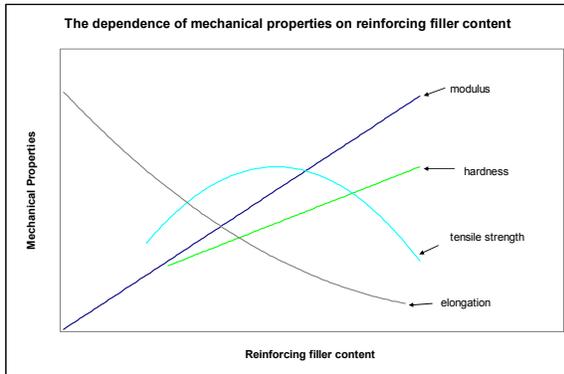
Figure 4: The Dependence of Mechanical Properties on Reinforcing Filler Content

B. Filler Surface Activity

The surface chemistry of fumed silica plays a significant role in determining many application properties. For non-treated fumed silica, the silanol groups on the surface make the filler hydrophilic. As the fumed silica is mixed into the silicone rubber, silanol groups form hydrogen bonds with the silicone polymer. The result is a thickening effect as the hydrogen bonds form, which can render a compound too stiff for processing. This thickening effect of the compound increases with storage time and is accelerated with increased storage temperature. Additionally, shear modulus of the cured silicone filled with non-treated fumed silica can be very high.

Therefore, the majority of fumed silica is silane treated to render it hydrophobic.

This treatment results in reduced silanol group density, and the fumed silica shows a different dispersion and thickening behavior compared to that of the hydrophilic types. Thus, dispersion is easier and the thickening effect is reduced.

C. Payne effect

The shear modulus of the filled silicone rubber under dynamic deformation is weakly dependent on the frequency of the deformation, but strongly dependent on the amplitude. An increase in strain amplitude leads to a decrease in shear modulus as demonstrated in Figure 5, which is known as the Payne effect[4, 5]. Shear modulus is dependent on the polymer network effect, hydrodynamic effect, in-rubber structure and the filler-filler interaction[5, 9]. The Payne effect mechanism has been explained by filler networking (filler-filler interaction)[7], the adsorption-desorption of the polymer-filler[8], and the disentanglement of bulk polymer from the rubber bound to the surface. Nevertheless, there still are remaining questions about the mechanism involved in the Payne effect[6].
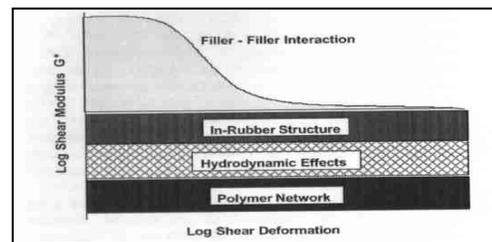
Figure 5: Idealized Form of a Typical Elastic Modulus Curve[5, 9]

VI. The effect of the extending filler system

Although silicone rubber has excellent thermal stability and elasticity, its thermal conductivity is too low (0.2W/mK) for most TIM applications. High thermal conductivity extending fillers are generally mixed into the silicone rubber matrix to increase the thermal conductivity[2]. This method can increase thermal conductivity values for a silicone TIM by greater than an order of magnitude. The extending filler must meet the following requirements: 1) High thermal conductivity. 2) Small particle size -- Small particle size is critical for mixing so that the elasticity of the matrix is not compromised. Most of the extending fillers are of the micron order. 3) Compatibility with the silicone rubber. 4) Electrically insulative or conductive -- depending on the application.

A. Filler content

In an electronic application, the PCB components continuously give off heat. This heat is conducted through the TIM, such as Arlon's Thermabond® adhesive, to the heat sink. A highly thermally conductive TIM is beneficial to the PCB because the thermal conductivity of the TIM (usually <10W/mK) is much lower than that of the heat sink (usually aluminum, Tc>200W/mK).

In order to obtain higher thermal conductivity for the TIM, extending fillers are added to the silicone rubber matrix. It has been found that the compound may crumble at filler content higher than a certain value. Additionally,

processing properties of the uncured compound and the mechanical properties of the cured TIM also change with increasing filler content. Even if there are no active sites on the extending filler surface for a reinforcement contribution, the mechanical properties of the cured TIM can change due to the hydrodynamic effect[4, 9]. In particular, the durometer and shear modulus increase with increased extending filler content.

B. Filler Surface Activity

The surface properties of the extending filler profoundly affect the interaction between the extending filler and the silicone polymer. The interaction between the extending filler and silicone affects interfacial thermal resistance. If the interaction between the extending fillers and silicone increases, the wetting of the silicone on the filler surface is better and, consequently, there is less interfacial thermal resistance. The interaction between the extending filler and the silicone also depends on the chemical structure of the silicone. The backbone of silicone rubber is always repeating units of silicon-oxygen, the side and end groups can be methyl, vinyl, phenyl, hydrogen, trifluoropropyl, or hydroxyl. These groups affect the interaction between the extending filler and the polymer.

As previously discussed, the extending fillers also have a reinforcing effect on silicone. If the interaction between the fillers and the silicone increases, the reinforcing effect of the extending filler becomes more significant.

C. Payne effect

As discussed in Section C of Part V above, extending fillers may also exhibit a Payne effect similar to that of the reinforcing fillers.

VII. Approaches to low shear modulus

Based on the above analysis, the following approaches can be applied to obtain a thermal interface material with low modulus.

- *Low crosslink density*
  Low crosslink density results in low shear modulus, but can also reduce tensile strength, shear strength, and bonding strength. When the crosslink density is kept as low as possible, other properties such as tensile strength, shear strength and bonding strength cannot be compromised. The crosslink density depends on the amount of curing agent, the quantity of active crosslinking sites on the polymer backbone, curing temperature, and curing time. The crosslink density can be determined by a solvent-swell test.
- *Optimal silicone molecular weight*
  Low molecular weight of silicone results in low modulus because there is less physical entanglement of the polymer chains. This, however, requires more chemical crosslink sites or a higher crosslink density to obtain acceptable strength for an actual TIM application.
- *Less reinforcing filler*
  In order to obtain low modulus, the content of reinforcing fillers should be as low as possible.
- *Less extending filler*
  The extending filler provides thermal conductivity. It also has a reinforcing effect on the silicone and increases shear modulus.

VIII. Summary

Low shear modulus of a TIM plays a crucial role in thermal-mechanical decoupling for electronic components (PCB/Heatsinks). It is a critical material property that can lead to long term electronic assembly reliability. Low shear modulus of a TIM can be realized via low polymer crosslink density, optimal polymer molecular weight, and selective use of reinforcing filler and extending filler systems. However, the low shear modulus material property goal must be balanced by the need for acceptable TIM shear strength and thermal conductivity. These properties are always driven by specific application requirements.

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