The Effects of Temperature and Aging on Young’s Moduli of Polymeric Based Flexible Substrates

Ron S. Li and Jinbao Jiao
Motorola Inc.
Automotive and Industrial Electronics Group
4000 Commercial Avenue
Northbrook, Illinois 60062
Phone: (847) 480-5674/4717
Fax: (847) 480 – 3344
e-mails: g11597@email.mot.com, g13990@email.mot.com

Abstract

Polymeric based flexible substrates are widely used as bendable Printed Circuit Boards in automotive and other electronic systems for easy interconnection and processing. Their flexibility however brings issues such as high dynamic stresses and dynamic fatigue associated with structural instability. Stress analysis and fatigue prediction requires fundamental understanding of thermal mechanical properties of these materials. This paper specifically studies the effects of temperature and aging on Young’s moduli of the flexible substrates and their components. The performance of the bulk substrate depends to a large extent on the selection of the core layer material which is the primary load-bearing structure in the flexible substrate. The tested core layers include polyethylene naphthalate (PEN), polyester (Mylar, PET), and polyimide (PI). Two types of copper traces and two types of traces deposited on different polymer films are studied under various temperature conditions. These samples include 1.4 mil electronic deposited (ED) copper, 1.4 mil rolled and annealed copper, 1.4 mil ED with 2 mil PET, and 1 mil A523 epoxy coating, and 1.4 mil vapor deposited and plated copper with 2 mil PI. Substrates with different compositions and manufacturing processes are experimentally studied on Dynamic Mechanics Analyzer under various temperatures from -40°C to 125°C. The corresponding components for each type of substrates are tested to identify key contributing factors in the material systems. Thermal aging effects on the Young’s moduli are analyzed accordingly. The volume fraction model for evaluating moduli of composite materials is shown to have good correlation with the experimental results. The comprehensive test results on these flexible substrates and their components not only provide a complete data set for design and analysis, but also provide some bases for failure analysis and reliability assessments.

Key words:
Flexible Substrates, Mechanical Properties, Temperature and Aging, and Thin Films.

1. Introduction

The capability of mechanical simulation and analysis in automotive industries has improved significantly. These improvements include computing resources, knowledge of simulation tools, understanding of materials, and development of fatigue life approaches1. The role of mechanical analysis has been shifted from identification of root causes to prediction of product capabilities and potential problems. Understanding of material behaviors is one of the key components in providing reliable results.
The Effects of Temperature and Aging on Young’s Moduli of Polymeric Based Flexible Substrates

The Effects of Temperature and Aging on Young’s Moduli of Polymeric Based Flexible Substrates

of capability prediction. Simulation results can provide high confidence to a design team only if they are based on accurate material data such as moduli, stress-strain curves, fatigue curves and fracture toughness.

Many applications of flexible substrates can be found in various literatures2-4. In the automotive electronic control modules, flexible substrate is used in a rather innovative ways in the PolyBent™ design where interconnection is achieved through its flexibility5-6. It is the flexible substrate that makes the unique folding process of the PolyBent™ products possible. Figure 1 shows the result of simulation of the folding process where the flexible substrate is formed through bending of its stiffening metal base-plate. Stiffness of the flexible substrate determines whether a desirable bending profile of the substrate can be formed properly. Hence, this work specifically focuses on measurement and analysis of Young’s moduli of several flexible substrates under various temperature and aging conditions. Substrates made of several core layers and from different manufacturing processes were experimentally studied on Dynamic Mechanics Analyzer with the temperature range of -40°C to 125°C. The corresponding components for each type of substrates were tested also to identify key contributing factors in the material systems. Thermal aging effects on the Young’s moduli are analyzed accordingly. Aged samples were prepared under different temperature and aging duration. Material strength and fatigue performance of flexible substrates are published in separate papers7-9.

Test sample was mounted vertically in the clamp. A film tension mode was used for the measurement. The sinusoidal oscillation force with a frequency of 1Hz was applied on the sample. The maximum amplitude was controlled to be 1% of the sample length. Temperature ramp was set from 125°C to cool down to -45°C at a rate of -5°C/min.

The measured results are the average values of storage modulus E’ at various temperatures, while those materials were deformed in tension under the periodic (oscillatory) stress. The storage modulus is reasonably equal to the Young’s modulus since the damping (energy dissipation) factor (tanδ = E’’/E’ ~ 0) in these materials are negligible11-12. Samples were also aged in oven at 150°C under air for 250, 500 and 1000 hrs to evaluate to effect of aging on the modulus change.

3. The Effects of Temperature

3.1. Moduli of Substrates Versus Temperature

Three substrates made of various core layers and from different processes were used for Young’s moduli measurements (designated as APLS, Palflex, and Sheldahl). The test sample is a simple strip of 0.787 inch x 0.2 inch. The overall thickness is 7 mils. There is one copper trace layer in it. The 20 mil traces are spaced 20 mil apart. There are four parallel traces. They are all polyimide based with difference in processing and metal deposition.
Young’s moduli of these bulk substrates were measured within the temperature range of -45°C to 125°C. The measured results are shown in Figure 3. At room temperature, Young’s modulus of polyimide based flexible substrates is roughly at 8 Gpa. The stiffness of the polyimide-based substrates reduces when temperature rises. Palflex seems to be the softest material among all three substrates. For all three sample types, the reduction in the value of Young’s modulus becomes noticeable at temperature above 80°C. Within the given temperature range of -45°C to 125°C, the value of Young’s modulus varies about 60% (see Table 1).

![Figure 3. Effect of temperature on the bulk substrates.](image1)

Table 1. Variation of Young’s moduli of bulk substrates over temperature -45°C ~ 125°C.

<table>
<thead>
<tr>
<th>Material</th>
<th>∆E</th>
</tr>
</thead>
<tbody>
<tr>
<td>APLS</td>
<td>-60%</td>
</tr>
<tr>
<td>Sheldahl</td>
<td>-55.5%</td>
</tr>
<tr>
<td>Palflex</td>
<td>-62.5%</td>
</tr>
</tbody>
</table>

3.2. Moduli of Core Layers versus Temperature

Polyimide core layer is the premier load-bearing structure in the flexible substrate. The performance of the bulk substrate depends to the large extent on the selection of the core layer material. Three types of core layer materials are tested. These core layers include Polyethylene Naphthalate (PEN), Polyester (Mylar, PET) and Polyimide (PI). Their thickness is 2 mils. Glass transition temperature of PEN, PET, and PI is 135°C, 110°C, and 300°C, respectively.

The test results are shown in Figure 4 where Film A, Film B, and Film C represent PEN, PET, and PI, respectively. At room temperature, the value of Young’s moduli is approximately at 3 to 4 Gpa. The stiffness of the core layer materials reduces when temperature rises. Among all three materials tested, polyimide (PI) film experiences the least temperature effect (see Table 2). It is also the softest material below 80°C, and therefore, it is easy to bend. Mylar (PET) film experiences dramatic softening approximately at 80°C. The result indicates that Mylar is not suitable for automotive under-hood applications where environment temperature is often above 105°C.

![Figure 4. Effect of temperature on Young’s moduli of core layers. Film A, B and C represent PEN, PET and PI, respectively.](image2)

Table 2. Variation of Young’s moduli of core layers over temperature -45°C ~ 125°C.

<table>
<thead>
<tr>
<th>Material</th>
<th>∆E</th>
</tr>
</thead>
<tbody>
<tr>
<td>PEN</td>
<td>-56.9%</td>
</tr>
<tr>
<td>PET</td>
<td>-78.6%</td>
</tr>
<tr>
<td>PI</td>
<td>-29.0%</td>
</tr>
</tbody>
</table>

3.3. Temperature Effects on Copper Traces and Copper Traces Deposited on Polymer Films

Previously observed field failures and vibration failures of the flexible substrates all initiated on the copper traces. It is important to understand how the material of the traces reacts to mechanical load and environment. Two types of copper traces and two types of traces deposited on different polymer materials were studied under different temperatures. These samples include 1.4 mil electronic deposited (ED) copper, 1.4 mil rolled and annealed copper, 1.4 mil ED with 2 mil PET, and 1 mil A523 epoxy coating. 

The measured values of Young’s moduli are given in Figure 3 for these four types of samples. Young’s modulus of the thin copper films is roughly at 50 Gpa to 60 Gpa while that of bulk copper is 130 Gpa. The stiffness of the copper material is reduced due to the film processing. ED copper has a higher stiffness than the RA copper. RA copper appears to be easy for bending due to its lower stiffness. However, ED copper was shown to have better ductility in a separate paper. Copper trace deposited on polyimide film has very stable stiffness over the temperature range of -40°C to 125°C. When deposited on Mylar film, the copper trace experiences reduction in stiffness above 50°C. These results are given in Figure 5.
The Effects of Temperature and Aging on Young’s Moduli of Polymeric Based Flexible Substrates

3.4. The Effects of Aging on Substrates

Samples of APLS, Palflex, and Sheldahl substrates were put in an oven under 125°C for temperature aging. Two sets of samples were prepared at the time duration of 500 hours and 1000 hours. Measurement of Young’s moduli was carried out for both sets of samples. The experimental results are shown in Figure 6.

Compared with the results given in Figure 3, Figure 6 indicates that temperature aging increases the stiffness of the substrates. This tendency is more pronounced for Palflex and Sheldahl. Aging at high temperature also closes the appearance of glass transition. That is, there is no significant change in modulus around the glass transition temperature. Temperature dependence of the aged materials becomes less significant than that of the virgin material.

Young’s moduli were measured for the two sets of samples aged for 500 hours and 1000 hours. The data were taken at -40°C, 25°C and 125°C. The results of these measurements are given in Figure 7 to Figure 9. On all three substrate materials, the effect of aging duration on the moduli is insignificant when measured at low temperature. When measured at high temperature, however, the value of Young’s moduli shows an increase as the duration of aging increases.
4. Effective Modulus of Composites

Presented in this work is the volume fraction model that allows quick estimation of effective Young’s modulus of laminate structures such as flexible substrates. If a specimen of laminate film is loaded by force $P$ in uniaxial direction, the total load $P$ is equal to summation of each individual load $P_i$ acting on every component of the structure (Figure 10), of the form,

$$ P = \sum_{i=1}^{N} P_i $$

(1)

The above equilibrium equation can be rewritten as follows,

$$ E_{\text{eff}} \epsilon_{\text{eff}} A = \sum_{i=1}^{N} E_i \epsilon_i A_i $$

(2)

Where $E$, $\epsilon$, and $A$ are Young’s modulus, strain, and area, respectively. Subscripts “i” and “eff” denote individual components and effective, respectively. If the bonding among the individual components is perfect, that is, there exists no slippage ($\epsilon_{\text{eff}} = \epsilon_i$), the compatibility conditions lead to the following,

$$ E_{\text{eff}} = \frac{\sum_{i=1}^{N} E_i A_i}{A} $$

(3)

The following two examples indicate that this simple model can provide fairly good estimation of Young’s modulus of laminate structures.

---

Example 1: 1 oz ED copper on 0.002 inch Mylar with 0.001 inch A523 coating at 0°C:

$$ E_{\text{eff}} = \frac{63 \times 1.4 \times w + 3 \times 2 \times w}{3.4 \times w} = 22.8 \text{GPa} $$

---

Example 2: 1 oz copper on 0.002 inch Polyimide film at 0°C:

$$ E_{\text{eff}} = \frac{63 \times 1.4 \times w + 3 \times 2 \times w}{3.4 \times w} = 27.7 \text{GPa} $$

In this case, $w$ represents the sample width. These results given in these two examples can be checked against the results shown in Figure 4.

5. Conclusion

Young’s moduli of three different flexible substrates and their components were characterized by using the Dynamic Mechanics Analyzer. The effects of temperature and aging on the Young’s moduli were also thoroughly studied. The test results can serve as a good resource for mechanical properties required in computer modeling and simulation. The trends of temperature and aging effects on the flexible substrates also provide a basis of understanding of actual failures of substrates in actual field applications.

A simple model that allows quick estimation of effective Young’s modulus of laminate structure such as flexible substrates is presented. Numerical results from that model correlate well with the measured results from experiments.

---

Acknowledgment

The authors would like to thank Larry Poglitsch for his support and advice to this project.

---

About the authors

Ron S. Li received his B.S. and M.S. Degrees in Aerospace Engineering from the Nanjing University of Aeronautics, and Astronautics in China in 1982 and 1985, respectively. He worked extensively on aircraft design and structural analysis in aerospace industries until 1991 at which time he departed McDonnell Douglas Aircraft Company to pursue his doctoral degree. He received his Ph.D. Degree in Engineering Mechanics from The University of Illinois in 1994, and joined
Motorola’s automotive group. He has been focusing on electronic packaging technologies at system and component level under severe vibration and thermal environments. He developed a systematic approach and computerized tools that allow placement of electronic components anywhere on the board for system vibration analysis and assessment of lead/solder joint reliability. He has been actively pursuing characterization of fatigue durability of flexible substrates, copper leads, and solder joints related to Ball Grid Array Packages, Flip Chips, Plastic Quad Flat Packages, and other electronic components. Most recently, he has completed fatigue reliability study of BGAs and QFPs in automotive electronic systems. He is currently working on reliability of ground connections and conductive traces in the application of thin FR-4 flexible circuitry under thermal shock conditions. He has authored and co-authored over thirty technical papers in refereed journals and conference proceedings.

Dr. Jinbao Jiao is a staff engineer at Motorola Inc. working on polymeric packaging in microelectronics. He completed his Ph.D. Degree in Polymer Chemistry and Materials Engineering from Cornell University (1997), Ithaca, New York. He also holds M.S. Degree in Polymer Chemistry from Cornell University (1994), M.S. Degree in Physical Chemistry (1987), and B.S. degree in Chemistry (1987) from Fudan University, China. He was with a faculty position at University of Science and Technology of China from 1987 to 1993 and a visiting scientist at University of Tokyo, Japan, from 1989 to 1990. He joined Motorola Integrated Electronics Solution Section (IESS), Northbrook, Illinois, in 1997. He has been engaged in the development and application of thermally conductive adhesives and electrically conductive adhesives for components and die attachment, flip chip underfills, fluoro polymers for encapsulants. He is currently involved in direct chip attach and flexible circuit technologies for automotive electronics with emphasis on materials characterization and qualification. His field of interest lies broadly on adhesives, plastics, encapsulants, sealant, and conformal coatings applied in various microelectronics technologies.

References