Predictive Analytical Thermal Stress Modeling in Electronics and Photonics

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We discuss the role and the attributes of, as well as the state-of-the-art and some major findings in, the area of predictive analytical ("mathematical") thermal stress modeling in electronic, opto-electronic, and photonic engineering. The emphasis is on packaging assemblies and structures and on simple meaningful practical models that can be (and actually have been) used in the mechanical ("physical") design and reliability evaluations of electronic, opto-electronic, and photonic assemblies, structures, and systems. We indicate the role, objectives, attributes, merits, and shortcomings of analytical modeling and discuss its interaction with finite-element analysis (FEA) simulations and experimental techniques. Significant attention is devoted to the physics of the addressed problems and the rationale behind the described models. The addressed topics include (1) the pioneering Timoshenko's analysis of bimetal thermostats and its extension for bimaterial assemblies of finite size and with consideration of the role of the bonding layer of finite compliance; this situation is typical for assemblies employed in electronics and photonics; (2) thermal stresses and strains in solder joints and interconnections; (3) attributes of the "global" and "local" thermal expansion (contraction) mismatch and the interaction of the induced stresses; (4) thermal stress in assemblies adhesively bonded at the ends and in assemblies (structural elements) with a low-modulus bonding layer at the ends (for lower interfacial stresses); (5) thin film systems; (6) thermal stress induced bow and bow-free assemblies subjected to the change in temperature; (7) predicted thermal stresses in, and the bow of, plastic packages of integrated circuit devices, with an emphasis on moisture-sensitive packages; (8) thermal stress in coated optical fibers and some other photonic structures; and (9) mechanical behavior of assemblies with thermally matched components (adherends). We formulate some general design recommendations for adhesively bonded or soldered assemblies subjected to thermal loading and indicate an incentive for a wider use of probabilistic methods in physical design for reliability of "high-technology" assemblies, including those subjected to thermal loading. Finally, we briefly address the role of thermal stress modeling in composite nanomaterials and nanostructures. It is concluded that analytical modeling should be used, whenever possible, along with computer-aided simulations (FEA) and accelerated life testing, in any significant engineering effort, when there is a need to analyze and design, in a fast, inexpensive, and insightful way, a viable, reliable, and cost-effective electronic, opto-electronic, or photonic assembly, package, or system. [DOI: 10.1115/1.3077136]

"Mathematical formulas have their own life, they are smarter than we, even smarter than their authors, and provide more than what has been put into them."
Heinrich Hertz, German Physicist

"A theory should be as simple as possible, but not one bit simpler."
Albert Einstein, German Physicist

"It is tough to make predictions, especially for the future."
Sam Goldwyn, American Film Mogul

1 Thermal Loading and Thermal Stress Failures

"*Reliability is when the customer comes back, not the product*."
Unknown Reliability Manager

From the structural analysis and structural reliability points of view, various areas of engineering (civil, maritime, aerospace, automotive, "high-technology," etc.) differ by (1) the types and variety of the employed materials, (2) typical structures used, and (3) the nature of the applied loads. The most typical electronic (micro or power electronic alike), opto-electronic, and photonic structures are multimaterial and/or composite structures comprised of a broad variety of dissimilar materials (see, as examples, structures in Figs. 1 and 2). As to the applied loads, it is the thermal loading that is of primary interest for, and is of major concern to, "physical" designers and reliability engineers in the field [1–9].

Steady-state or transient thermal loading in electronic and photonic equipment is due to (1) the thermal expansion/contraction mismatch of the dissimilar materials in the system and/or to (2) the nonuniform distribution of temperature (temperature gradi-

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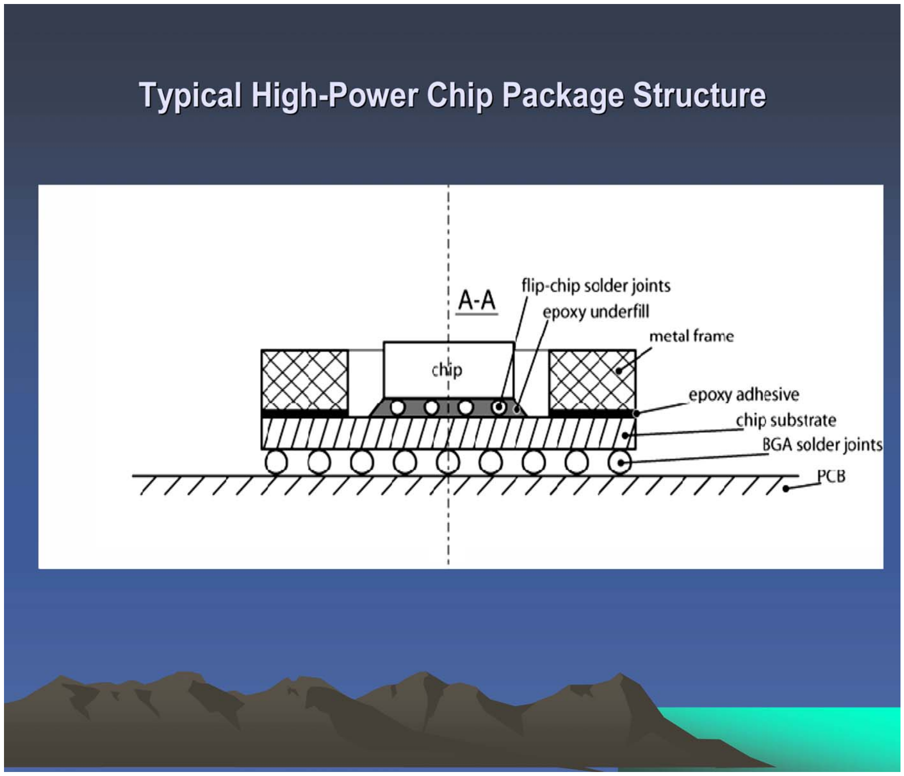

Fig. 1 Typical high-power flip-chip package structure

ents). It is quite typical that electronic and photonic structures are being subjected to the combined and concurrent action of thermal, mechanical, and dynamic loads.

Thermal loading takes place during the normal operation of electronic and photonic assemblies, structures, packages, equipment, and systems, as well as during their fabrication, testing, transportation, or storage. The induced stresses, displacements, and strains can be linearly or nonlinearly elastic (reversible), or plastic (residual and irreversible), or elastoplastic (partially reversible). In many modeling efforts one could assume that the structural response is instantaneous, so that the time-dependent effects need not be considered in a particular practical situation. In some other cases (e.g., for epoxy adhesives or solders) time-dependent effects might be important, and the effect of time-dependent phenomena (creep, stress-relaxation, plastic flow, visco-elasticity or viscoplasticity, aging, etc.) on thermal stresses should be taken

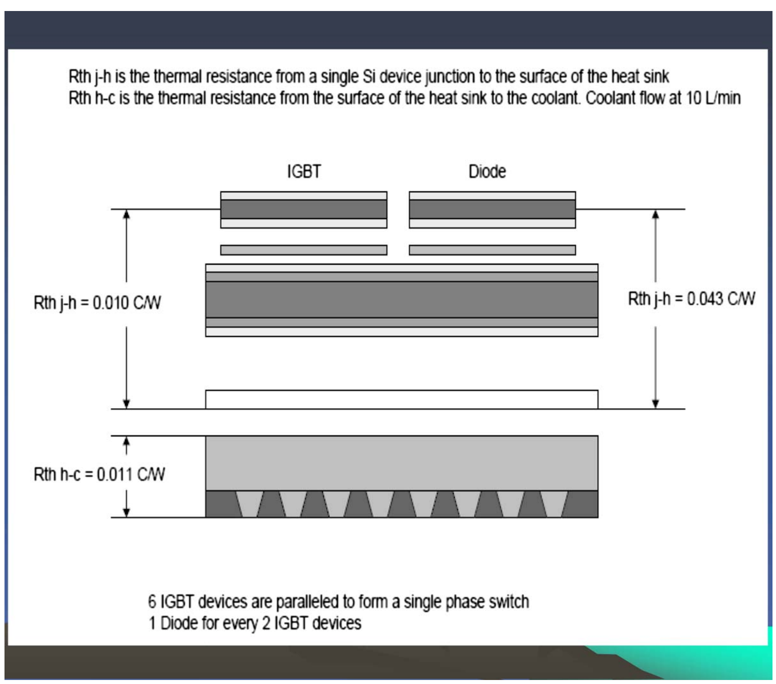

Fig. 2 Typical multimaterial assembly for a high-power electronic module

into consideration. One should always make sure, however, before introducing a more complicated (plastic, time dependent, nonlinear, etc.) model that the simplest linearly elastic model is not sufficient for a particular application.

Thermal stresses, strains, and displacements are the major contributors to today's structural (mechanical and physical) and environmental failures of the equipment. Examples of such failures are ductile rupture, brittle fracture, thermal fatigue, elevated creep, excessive deformations (these are especially important in optoelectronic and photonic systems), stress-relaxation (these might lead to excessive undesirable displacements), stress corrosion, and material degradation.

Thermal stresses, strains, and displacements can lead not only to mechanical (physical) failures but also to functional (electrical, optical, thermal) failures. If the heat, produced by the chip, cannot readily escape, then the high thermal stress in the integrated circuit (IC) can result in the failure of the *p-n* junction [10]. Low-temperature microbending (buckling of the glass fiber within the low-modulus primary coating) in dual-coated optical fibers, although might be insignificant to lead to appreciable bending stresses and subsequent delayed fracture ("static fatigue") in the silica material, can nonetheless result in appreciable added transmission losses [11]. Complete loss in optical coupling efficiency can occur when the displacement in the lateral (often less than 0.2 μm) or angular (often less than a split of 1% of a degree) misalignment in the gap between two light-guides or between a light source and a light-guide becomes too large. This is often due either to the thermally induced deformations or to the thermal stress-relaxation in a laser weld. Small lateral or angular displacements in microelectromechanical systems (MEMS)-based photonic systems (such as, say, some types of tunable lasers) can lead to a complete optical failure of the device. Tiny temperature-induced changes in the distances between Bragg gratings "written" on an optical fiber can be detrimental to its functional performance. For this reason thermal control of the ambient temperature is sometimes needed to ensure sufficient protection provided to an optical device sensitive to the change in the ambient temperature. It should be emphasized that the requirements for the mechanical (physical) behavior of the materials and structures in optoelectronic and photonic structures are often based on the functional (optical) requirements (specifications). The requirements for the structural reliability or for the environmental durability might be significantly less stringent. In other words, if one takes care of the effect of the thermal stress related phenomena on the optical performance, the mechanical (physical) performance "will take care of itself."

The ability to understand the sources and causes of the thermal stresses and strains in electronic and photonic structures is important, as is the ability to predict (model) and possibly minimize the adverse effects of thermally induced stresses and deformations in electronic and photonic systems.

2 Thermal Stress Modeling

"Vision without action is a daydream. Action without vision is a nightmare."
Japanese Saying

Modeling is the basic approach of any science, whether "pure" or applied. Research and engineering models can be experimental or theoretical. Experimental models are typically of the same physical nature as the actual phenomenon or the object. It is well known that an experimental vehicle (setup) should be geared to the phenomenon that the experimentalist intends to observe and investigate. Theoretical models represent real phenomena and objects by using abstract notions. Theoretical models can be either analytical ("mathematical") or numerical (computational). Analytical models typically employ more or less sophisticated mathematical methods of analysis. Today's numerical models are, as a rule, computer aided. Finite-element analysis (FEA) is widely used in the stress-strain evaluations, and physical design of electronic and photonic systems. Experimental and theoretical models should be viewed as equally important and indispensable tools for the design of a viable and reliable device and making it into a marketable cost-effective product.

Thermal failures in electronic and photonic materials, components, devices, and equipment can be predicted and prevented only if adequate theoretical modeling, whether computer aided or analytical, is consistently used in addition and desirably prior to experimental investigations and reliability testing [12–17]. Accelerated testing, which is the major experimental approach in electronics and photonics, cannot do without predictive modeling. This is particularly true about accelerated life testing (ALT). It is on the basis of modeling that a reliability engineer decides which parameter should be accelerated, how to process and interpret the ALT data, and how to bridge the gap between what one "sees" as a result of such testing and what he/she will supposedly "get" in the actual use conditions.

Analytical modeling occupies a special place in the modeling effort. Analytical modeling is able not only to come up with relationships that clearly indicate "what affects what and what is responsible for what" but, more importantly, can often explain the physics of the observed or anticipated phenomena. Neither the FEA nor even the actual experimentation might be able to do that, especially when there is a need to explain a paradoxical situation. It was not obvious, for instance, in the mid-1980s that the thermal stress does not increase infinitely with the increase in the size of a bimaterial assembly, nor that the interfacial stresses concentrate at the assembly ends, until these phenomena were addressed and explained on the basis of analytical modeling [18–25]. The fact that compliant leads could reduce the strength of a surface mounted device was detected experimentally first, but could be explained only on the basis of analytical modeling [26]. When the mechanical behavior of a dual-coated optical fiber was analytically evaluated based on the theory of beams lying on elastic foundations, it has been found that a similar situation takes place in dual-coated fibers and therefore the curvature of the coated glass fiber might be different from the observed (measured) curvature of its coating [27]. Recently, it has been detected using FEA simulations that deliberately introduced transverse grooves in the adherends of a small-size lap shear joint could reduce considerably the interfacial mechanical stresses in it, but it is only on the basis of an analytical modeling that this situation was explained [28].

Analytical modeling has, however, one important "shortcoming:" it is never straightforward and requires, as a rule, in-depth understanding of the physics and mechanics of materials in the phenomenon of interest, good intuition about the possible role of different factors affecting the structure or the phenomenon under investigation, and versatile knowledge and skills in applied mathematics, applied physics, and applied mechanics. It requires quite often also extraordinary creativity. As Einstein put it, it is not easy to create a meaningful and practically important analytical model that is "as simple as possible, but not one bit simpler."

There is always a temptation in trying to consider everything that seems to have an effect, even a minor, on the phenomenon or a structure of interest (nonlinearities, time-dependent effects, higher modes of vibrations, etc.). The right approach, however, is to take one step at a time and to build a more complicated model after a more simple model is developed, implemented, and thoroughly analyzed (e.g., by comparing FEA, experimental, and analytical data), and when there is a strong evidence that a model that is "as simple as possible" is too simple to address a particular situation of interest.

Pioneering work in modeling of thermal stress in bodies comprised of dissimilar materials was conducted back in 1925 by Timoshenko [29] based on the strength-of-material (structural analysis) approach and by Papkovich [30] and Aleck [31] who applied theory-of-elasticity methods. Only what we call today "analytical modeling" existed at that time: FEA and other computer-aided techniques were developed much later, in the late 1950s. It is noteworthy that Timoshenko published his classical article in the Journal of the Optical Society of America. Papkovich, an outstanding Russian naval architect and stress analyst, evaluated the thermal stresses in a multimaterial thick-walled tube. He used Lame's theory-of-elasticity solution for a thick-walled tube subjected to internal and/or external pressure. Aleck addressed the stress-concentration at the end of a rectangular plate clamped along its edge and subjected to the temperature change. Both the structural-analysis-based and the theory-of-elasticity-based approaches were later on extended and advanced by numerous investigators in application to assemblies and systems employed in various fields of engineering, including the area of electronics and photonics.

The state-of-the-art in the mathematical theory of thermal stresses (regardless of a particular application) can be found in the book by Namson [32], in the classical monograph by Boley and Weiner [33], as well as in the recently published books by Noda et al. [34], Ceniga [35], and Lanin and Fedik [36]. The current state of knowledge in the field of thermal stress in electronic equipment, including modeling, has been addressed by Lau [1] (see also the author's review chapter [37]).

3 Bimetal Thermostats

"The man who removes a mountain begins by carrying away small stones."
Chinese Proverb

Timoshenko [29] addressed the thermal stress problem in application to bimetal thermostats. In his time these structural elements were widely used in temperature control devices. Timoshenko suggested a simple and effective analytical model for evaluating the thermostat bow and the normal stresses in the cross sections of the thermostat strips. Timoshenko's model proved extremely useful for many applications in electronics and photonics. It is referenced therefore in numerous publications. There are nonetheless several essential differences between the structure of a bimetal thermostat addressed by Timoshenko and bimaterial assemblies employed in electronics and photonics.

First of all, a thermostat structure is expected to be highly flexible and highly sensitive to the change in temperature. In other words, it is supposed to be prone to significant bending deformations caused by even small "external" thermal strains. These strains are products, $\Delta\alpha\Delta T$, of the difference, $\Delta\alpha$, in the coefficients of thermal expansion (CTEs) of the materials of the thermostat strips and the change, ΔT, in temperature. On the contrary, the overwhelming majority of electronic and photonic assemblies are characterized by significant flexural rigidities. Appreciable bending deformations, if any, in such assemblies are viewed, as a rule, as a shortcoming of their behavior and performance.

Second of all, the bimetal thermostat materials are quite different from the materials employed in electronic and photonic structures, and so is their propensity to failure. Metals, employed in bimetal thermostats, are among the best structural materials, while silicon and other semiconductors (Ge, GaAs, InP, GaN, etc.) used in electronics and photonics are perhaps among the worst. The same is true for optical silica glasses. The mechanical behavior and performance of various polymeric materials or solders are also quite different from the bimetal thermostat strip materials.

However, the most important difference between a bimetal thermostat and an electronic or a photonic assembly has to do with the state of stress in these structural elements and their response to thermal loading. Bimetal thermostat experiences significant bow because of the deliberately introduced considerable CTE mismatch of the strip materials. Therefore the thermal stress related response, which is of primary concern, is the normal (bending) stress in the cross sections of a thermostat strip. This stress is the highest in the significant midportion of the structure and drops to zero at its ends. On the contrary, materials with a low CTE and a low CTE mismatch with silicon or with silica glass are desirable in electronic and photonic assemblies. The CTE of silicon is about 2.4 ppm/°C and the CTE of silica material is as low as 0.5 ppm/°C. A good thermal match with these core materials is needed for low thermal stresses. The induced bowing of an electronic or a photonic assembly or a coated optical fiber is small indeed. The main concerns are usually the interfacial shearing and peeling stresses. These stresses concentrate at the assembly (optical fiber interconnect) ends, can be quite high, and might lead to an adhesive or to cohesive failure of the bonding material and/or to cracks in the chip (at its interface with the substrate) or in the photonic package [38,39].

Neither the effect of the assembly size nor the interfacial stresses were addressed in Timoshenko's paper. The only comment that Timoshenko made in his article, as far as these stresses were concerned, was that they could not be addressed in an elementary fashion, i.e., on the basis of the strength-of-material (structural analysis) approach (employed by Timoshenko), and that a theory-of-elasticity treatment of the problem was needed to evaluate these stresses. Timoshenko's advice was fulfilled 24 years later by Aleck [31].

4 Bimaterial Assemblies

"A theory without an experiment is dead. An experiment without a theory is blind."
Unknown Physicist

The problem of thermal stresses in thermostatlike assemblies of finite length, including the interfacial stresses, was addressed in connection with the needs of the electronic industry [18–24,40–50], in the late 1970s to early 1980s. Chen and Nelson [42], Chen et al. [43], Chang [44], and Suhir [18–21] used the strength-of-materials (structural analysis) approach. The latter author employed, within the framework of such an approach, Ribiere's theory-of-elasticity solution for a long and narrow strip to evaluate the interfacial compliances in a bimaterial assembly. The use of the concept of the interfacial compliance enables one to evaluate the interfacial stresses on the basis of a strength-of-material (structural analysis) approach and to separate the loading-condition factors from the structural and material factors. The rationale behind this model is shown in Fig. 3. The cross sections of the components of a bimaterial assembly experience deviations from planarity in the vicinity of the interface. These deviations are accounted for by considering the interfacial displacements rather than strains (as has been done in Timoshenko's analysis) and by introducing into the equations for the interfacial displacements an additional term, a product of the predetermined interfacial compliance, and the sought interfacial shearing stress. This term is actually a "correction" to the expressions for the longitudinal displacements that accounts for the fact that the interfacial longitudinal displacements of the bonded components are somewhat larger than the displacements of the inner points of the cross sections, determined on the basis of Hooke's law. The model was able to describe, explain, and quantify the concentration of the interfacial stresses at the assembly ends. Being an approximate structural analysis model, it does not lead to a singularity at the ends of the assembly. The finite (not singular) maximum interfacial shearing stress at the end of the assembly should be viewed (interpreted), from the theory-of-elasticity point of view, as a sort of an integral characteristic of the state-of-stress at the end of the assembly. This characteristic could be used (e.g., at the product development stage) to compare different structures and materials in a design of interest. With an exception of the very end of the assembly, FEA computations show reasonably good agreement between the data predicted on the basis of the suggested model and the FEA results.

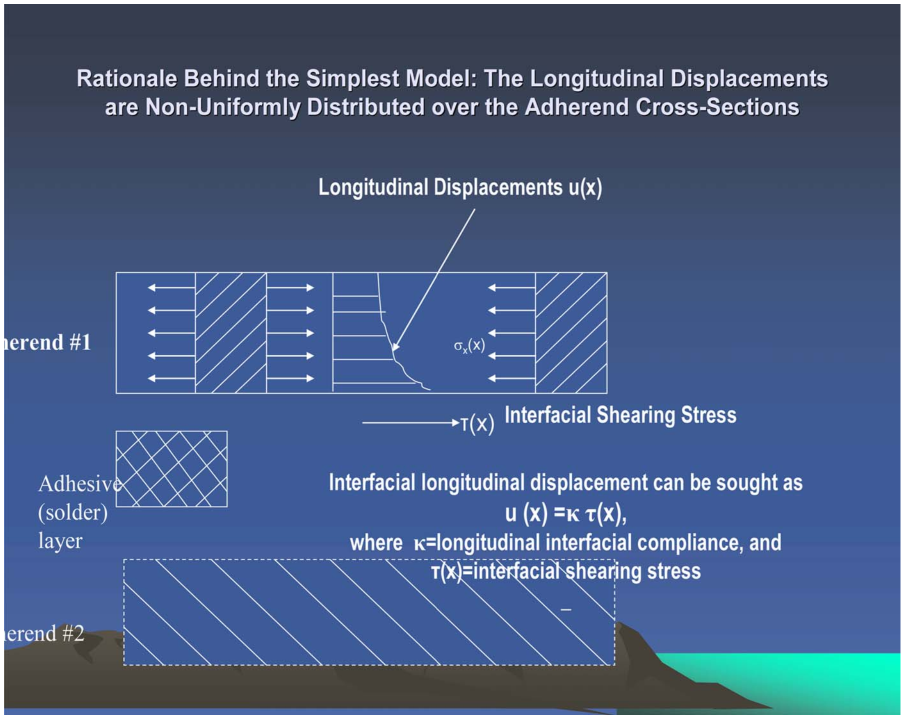

Fig. 3 Rationale behind the simplest analytical thermal stress model for a bimaterial assembly

Zeyfang [40], Grimado [41], Chen et al. [43], Kuo [22], Eischen et al. [23], and others used the theory-of-elasticity to address the problem in question. Their take was partially due to the fact that the theory of elasticity approach, with the emphasis on various types of singularities at the boundaries (edges and corners) of dissimilar materials, was rather well developed by that time, regardless of particular loading conditions or particular engineering situations, mostly in application to fracture mechanics problems. The fundamental work in fracture mechanics of multimaterial bodies was due to the classical and pioneering publications of Eshelby in the UK, Cherepanov in Russia, and Hutchinson and Rice in the USA.

Analytical stress models developed using structural analysis approach enable one to determine, often with sufficient accuracy and always with extraordinary simplicity, all the categories of stresses acting in bimaterial assemblies. These stresses include the normal stresses acting in the cross sections of the assembly components as well as the interfacial shearing and peeling stresses (i.e., the normal stresses acting in the through-thickness direction of the assembly). The structural analysis approach resulted in simple closed form solutions and easy-to-use formulas (see, for instance, Refs. [18–21]). This approach can be, and, actually, has been, employed in the physical design effort when selecting, at the product development stage, the appropriate materials; when establishing the adequate dimensions of the structural elements; and when comparing different designs from the standpoint of the expected or occurred thermally induced stresses, deformations, etc.

On the other hand, theory-of-elasticity, which is based on rather general hypotheses, equations, and relationships of mathematical physics, is in principle able to provide rigorous and well-substantiated solutions to almost any problem of interest. The theory-of-elasticity approach is advisable when there is a need for the most accurate evaluation of the induced stresses and deformations or when one wants to check the accuracy of the structural analysis results. The theory-of-elasticity approach often leads to a singularity at the assembly edges. For this reason its application has been found particularly useful when there is intent to proceed with the fracture analysis to evaluate or predict delaminations, determine the conditions for the crack initiation and propagation, etc. This statement is also true as far as FEA is concerned: this simulation technique is, in effect, a numerical implementation of one of the variational methods in the theory-of-elasticity. An important feature of a theory-of-elasticity (or plasticity) based approach is that the analytical results obtained on its basis might be so complicated that the subsequent employment of computers might be necessary to obtain the solution to a practical problem of interest.

Summarizing the above discussion, we would like to point out that if the solution to a particular problem could be obtained by using the theory of elasticity, it should be obtained this way. In many practical problems, however, the theory of elasticity leads to complicated and cumbersome expressions, from which it might be hard to understand the physics and the role of various factors affecting the characteristic of interest. If easy-to-use formulas cannot be obtained by using theory of elasticity, additional simplifying assumptions have to be made to, in one way or another, come up with a solution to a particular practical problem, and strength-of-materials (structural analysis) methods have to be used to obtain an acceptable engineering solution to a practical problem. As the famous Russian structural analyst, Papkovich, put it in the late 1930s, "the theory of elasticity can be successfully applied only to those problems that could be solved by using its methods. If it happens, the obtained solutions are as they should be. Strength of materials methods, on the other hand, can be applied to any problem that has to be solved, but the obtained solution is only as good as it gets."

The structural analysis (strength-of-materials) and theory-of-elasticity approaches should not be viewed as "competitors" but rather as different analytical tools with their own merits and shortcomings, and areas of application. These two analytical approaches should complement each other in any thorough engineering analysis and physical design effort. Both approaches should be carried out whenever possible and appropriate in addition to the FEA simulations.

5 Die-Substrate Assemblies

"It is always better to be approximately right than precisely wrong."
Unknown Design Engineer

Die-substrate assemblies occupy a special place among bimaterial structures in electronics and photonics. This is in part because one of the assembly components is a low-expansion and a brittle semiconductor material. The mechanical behavior of adhesively bonded die-substrate assemblies was addressed in numerous studies (see, for instance, [19,20,40,42,45,51–55]). Analytical stress models suggested for such assemblies in Refs. [19,20] can also be used, with some modifications, in flip-chip (FC) systems, including those with underfills. These are epoxy adhesives brought in into the underchip cavity to relieve the thermal loading on solder joints. To apply the models [19,20] one should "homogenize" the adhesive-solder composite structure so that a material with an "equivalent" Young's modulus is considered.

The models [19,20] address the following major failure modes encountered in adhesively bonded or soldered assemblies: (1) adherend (die or substrate) failure: a silicon die can fracture in its midportion or exhibit cracks at its corners located at the interface; (2) cohesive failure of the bonding material (i.e., a crack in the body of the die-attach material); and (3) adhesive failure of the bonding material (i.e., failure/delamination at the adherend/adhesive interface). It is widely accepted that an adhesive failure should not occur in a properly fabricated assembly. If such a failure takes place, it typically occurs at a low loading level, is usually detected at the product development stage, and is regarded/viewed as a manufacturing or a quality control problem rather than the material's or structural deficiency. All the stress categories are low at the manufacturing temperature and are the highest at low temperatures, primarily because of the temperature differential and partially because of the increase in Young's moduli of some materials at low-temperature conditions.

A crack, if any, on the upper ("free") surface of the die should be attributed to the excessive normal stress acting in the die cross sections at these conditions. If such a crack is observed, it means that the tensile stresses caused by the convex bending of the assembly exceed the compressive stresses caused by the thermal contraction mismatch of the (high-expansion) substrate and the (low-expansion) die. The compressive thermally induced stress is more or less uniformly distributed throughout the length of the die and drops to zero at its ends at the distances comparable with the die thickness (say, 0.5 mm or so). The crack at the die's corner, at its interface with the substrate, should be attributed to the elevated interfacial (shearing and "peeling") stresses, which concentrate at the assembly ends.

Measures that could be taken to reduce, if necessary, the thermal stresses depend on the type/category of the stress "responsible" for a particular failure mode. In the case of a crack in the die in its midportion, it is the improved thermal match between the die and the substrate materials and/or the reduced bow of the assembly that might improve the situation. Ceramic substrates, although more expensive than polymeric ones, are preferable not only because ceramics are inorganic, and, hence, more robust and moisture-penetration-resistant materials, but primarily because their CTEs are low, only 5–7 ppm/°C. For this reason, they have a better thermal match with silicon, whose CTE is about 2.4 ppm/°C. Lower bow of the assembly can be achieved by using a thick substrate (with a high flexural rigidity) or by going in the opposite direction and using a thin and a highly flexible substrate. In this case it is the die that is the rigid structural element of the assembly. As to the crack at the die's corner, it is due to the interfacial stresses that concentrate at the assembly ends. These stresses can be made lower by employing substrates with a better thermal match with the die, by using thicker bonding layers, and/or by employing low-modulus adhesives (i.e., epoxies with low glass-transition temperatures) for higher interfacial compliance.

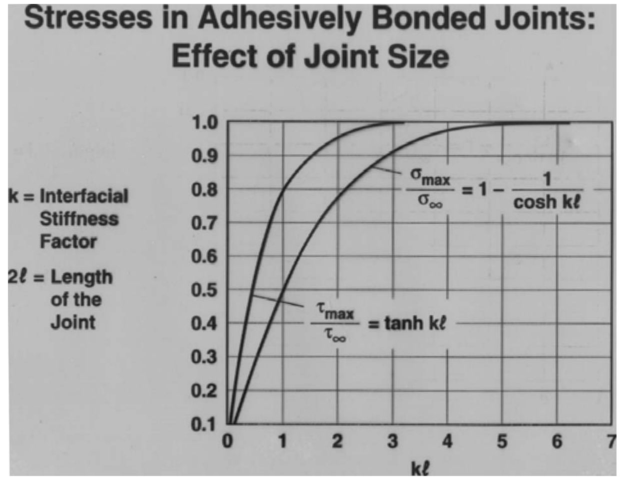

Fig. 4 Effect of the parameter of the shearing stress (stiffness factor) and the assembly size on thermal stresses

The thermal stresses in small-size assemblies (e.g., those with chips, not exceeding, say, 5–7 mm in size) increase with an increase in the assembly size and with a decrease in the compliance of the attachment (Fig. 4) [19,20]. The increase in the assembly compliance can result in such assemblies in lower stresses not only at the interface but in the adherends (assembly components) as well. Thermally induced stresses in sufficiently large assemblies (larger than, say, 8–10 mm) do not increase with a further increase in the assembly size, and the stresses in the vulnerable component of the assembly, such as silicon die, cannot be reduced by increasing the compliance of the bonding layer. Therefore other measures should be taken for large dies if there is a need to bring down the thermal stress in their midportion: a substrate material with a better match with silicon should be used; or a die-attach material with a lower curing temperature (and/or lower glass-transition temperature) should be employed; or application of a flexible substrate might be considered, etc. As to the interfacial shearing and peeling stresses in large-size assemblies, the application of a compliant (thick and low-modulus) bonding material can still reduce these stresses. This effect is, however, not as strong as in small-size assemblies.

It has been found that the product, ka, of the parameter k of the interfacial shearing stress and half-the-assembly-size a can be used as a suitable criterion ("figure of merit") of the effect of the assembly size and the assembly compliance on the level of the thermal stresses (Fig. 4) [19,20]. When this product is below 3.0–4.0, the assembly can be viewed as a small-size assembly. In the region $ka \leq 3.0-4.0$ the stresses of all the categories decrease with a decrease in the assembly size and an increase in the interfacial compliance. In the region $ka \geq 3.0-4.0$ the assembly size does not affect the thermally induced stresses, and the increase in the interfacial compliance does not change the maximum stress in the assembly components. The interfacial stresses, however, can still be reduced by increasing the compliance of the attachment. The parameter k of the interfacial shearing stress can be determined as $k=\sqrt{\lambda/\kappa}$, where λ is the total axial compliance of the assembly (i.e., the compliance of the assembly with respect to a tensile force applied to both components in the same direction) and κ is the total interfacial compliance of the assembly (i.e., the compliance with respect to the shearing forces applied, in the opposite directions, to the assembly components and resulting in the shearing stress at the interface). In conventional assemblies, with high-modulus and thick adherends and with a low-modulus and thin adhesive layer, the axial compliance λ is due to the adherends only, while the interfacial compliance κ is due to both the adherends and the adhesive. The formula $k=\sqrt{\lambda/\kappa}$ indicates, particularly, that the parameter k of the interfacial shearing stress and the interfacial stress itself decrease with a decrease in the axial compliance (of the adherends) and with an increase in the interfacial longitudinal compliance (of the adhesive). In other words, the best results, in terms of the low thermally induced stresses, can be achieved in assemblies with rigid adherends and compliant adhesives.

The interfacial compliance κ is expressed differently [19,20,25] depending on whether the thickness-to-length ratio of the bonding layer is small or large. For thick bonding layers and short assemblies, the interfacial compliance κ is proportional to the assembly size and is independent of the thickness of the bonding layer. In the case of thin bonding layers and large-size assemblies, the interfacial compliance κ is proportional to the thickness of the bonding layer and is assembly size independent. In both cases the interfacial compliance κ is inversely proportional to the shear modulus of the material.

The models [19,20] indicate that the interfacial shearing stress can be obtained as a derivative of the thermally induced forces in the assembly adherends with respect to the distance from the assembly midportion and are proportional therefore to the derivative of the normal stress acting in the adherend cross-sections. In the midportion of the assembly, where the normal stresses in the adherends are more or less constant along the assembly, the shearing stress is next to zero. The shearing stresses concentrate at the assembly ends, where the normal stresses in the assembly components reduce from their maximum value to zero.

The Timoshenko model [29] can be obtained as a special case of the finite-assembly-size model [19,20] when the assembly is infinitely long, and/or when the interfacial compliance is zero.

Note that the general equations for the shearing and the peeling interfacial stresses are coupled [21]. It has been shown, however [47], on the basis of both analytical modeling and FEA that, in an approximate analysis, the interfacial shearing stress can be evaluated using a simplified assumption that this stress is not affected by (i.e., not coupled with) the peeling stress. It has also been shown that such an assumption is conservative, i.e., results in a reasonable overestimation of the maximum shearing stress. After the shearing stress is determined, the peeling stress can be computed from an equation that is similar to the equation of bending of a beam lying on a continuous elastic foundation (see, for instance, Ref. [25]). The right part of this equation (the "loading"/"excitation" force) is proportional to the derivative, $\tau'(x)$, of the interfacial shearing stress, $\tau(x)$, with respect to the longitudinal coordinate x: highly concentrated at (rapidly increasing toward) the assembly ends interfacial shearing stress leads to higher peeling stress. Since the interfacial shearing stress $\tau(x)$ is proportional to the longitudinal gradient of the normal stress, $\sigma(x)$, in the assembly components, the interfacial peeling stress, $p(x)$, is proportional therefore to the second derivative (with respect to the distance from the assembly cross section) of the stress, $\sigma(x)$, with respect to the longitudinal coordinate x.

6 Other Applications of the Developed Models

"The practical value of mathematics is, in effect, a possibility to obtain, with its help, results simpler and faster."
Andrey Kolmogorov, Russian Mathematician

The models [19,20] were applied by numerous investigators to many problems in electronics, photonics, and beyond these areas of engineering.

Luryi and Suhir [56] suggested a new approach to the high quality (dislocation free) epitaxial growth of lattice-mismatched materials in hetero-epitaxial structures. Lattice-mismatch strain plays in such structures the same role as the external thermal strain, $\Delta\alpha\Delta T$, plays in thermally mismatched assemblies. Therefore the lattice-mismatch strain can be simply added, if necessary, to the thermal-mismatch strain and, owing to that, can be easily and naturally incorporated into the stress analysis models intended for thermally induced strains. Lattice-mismatched structures experience also thermal mismatches and are subjected therefore to both stress/strain categories. The publication [56] triggered a substantial experimental effort and numerous publications: more than 200 citations of it could be found in literature. It is still widely referenced in the physical literature.

Suhir and Sullivan [57] developed an axisymmetric version of the model suggested in Ref. [18] and applied it for the experimental evaluation of the adhesive strength of epoxy molding compounds used in plastic packaging of IC devices. Suhir [19] and Cifuentes [58] generalized the model [18] for the situation when the bonding material at the assembly ends exhibits elasto-plastic behavior. Fan et al. [59] used the concept of free-edge energy and the model [18] to predict delaminations in a bimaterial system. Wen and Basaran [60] and Jong and Chang [61] applied the analytical model [18] to multimaterial assemblies. Klein [62] applied "Suhir's analytical method for assessment of interfacial stresses in multilayered structures" and developed "relevant formulas to the mitigation of the impact of thermoelastic stresses in diamond coated ZnS windows." Sujan et al. [63] applied "the existing uniform temperature model proposed by Suhir… to account for different temperatures of the layers by incorporating a temperature ratio parameter" and come up with "a correction factor to Suhir's model." Hsu et al. [64] applied "digital photo-elastic and finite-element methods… to clarify the interfacial stresses predicted by Suhir's theories" and discussed the distributions of the thermal stresses in the adherends calculated by Suhir and Timoshenko's theories."

Suhir [24] considered a bi-material assembly with a "piecewise-continuous" bonding layer and showed how the obtained "theorem of three axial forces" could be used to design an assembly with low interfacial shearing stresses. Low shearing stresses will certainly result in lower peeling stresses as well.

Hall et al. [65] were the first to apply the analytical model [18] to trimaterial assemblies. An adhesively bonded (or soldered) assembly should be treated as a trimaterial one if the bonding layer is not thin compared with the thickness of the adherends and/or if its Young's modulus is not significantly lower than Young's moduli of the adherend materials. In such a situation the CTE of the bonding material and, of course, the normal stresses acting in its cross-sections should be accounted for.

An analytical model for a trimaterial assembly, in which all the materials are treated as "equal partners" of the assembly, was developed in Ref. [66]. In this model the geometries (thicknesses) of all the assembly components and the material's properties (elastic constants and CTEs) of all the materials are equally important. If a compliant bonding layer is employed at one or at both interfaces of a trimaterial assembly, then this circumstance could be accounted for in the same fashion as it has been considered in a bimaterial assembly, i.e., by increasing the interfacial compliance due to the bonded materials themselves with the increased interfacial compliance of the particular bonding layer. As long as such a layer is thin and/or is made of a low-modulus material, it does not experience appreciable normal stresses acting in its cross sections so that the assembly still remains a trimaterial body.

Thermal stresses in plated through-hole (PTH) structures were first analyzed by Bhandarkar et al. [67]. Like in other bimaterial assemblies in electronics, these stresses are particularly high at the ends of the PTH structures. Suhir and Savastiuk [68] examined the case of disklike copper (Cu) vias. The mechanical behavior of such vias was modeled on the basis of the theory of the elastic stability of circular plates subjected to compressive stresses. These stresses arise because of the thermal expansion mismatch of the Cu and Si materials at elevated temperatures. The authors calculated also the effect of the interaction of the stress fields on the Si wafer produced by many closely located vias. Bjorneklett et al. [51] evaluated thermomechanical stress and thermal cycling fatigue of chips adhesively bonded "back side" to their substrates. Peterson et al. [52], Zhao et al. [53], and Gao and Zhao [54] carried out a similar analysis for flip-chip assemblies. Huang et al. [55] addressed thermal stress induced voiding in electronic packages. Zhu et al. [69] addressed thermal stress in embedded power modules. In connection with this publication we would like to point out that our review addresses mostly micro-electronic systems. Power electronic systems are at least equally important. These systems are especially important in hybrid automotive modules. In principle, however, the models developed in application to micro-electronic systems, in which weak electrical currents carry information, can also be applied in power electronics, where electrical currents carry power. The major difference is in the level of the thermal stresses, the heat removal means, and in the means to ensure sufficient robustness of the system. Particularly, solder materials that operate in the region of low-cycle fatigue might not be advisable in high-power systems, especially when variable temperatures and significant nonthermal (i.e., dynamic) loading take place. Lord [70] carried out thermal stress analysis for semiconductor wafers in rapid thermal processing ovens, where significant temperature gradients might take place. Riddle [71] evaluated thermal stresses in microchannel heat-sinks cooled by liquid Ni.

Significant effort has been dedicated to the application of fracture mechanics to various thermal stress modeling problems, including those in electronics and photonics. In this review we will only mention just a few publications in this field. Riddle [72] applied Rice's *J*-integral to evaluate fracture under mixed (normal and shear) loading, not necessarily thermal. Gillanders et al. [73] applied the developed methodology to the case of thermal loading. John et al. [74] evaluated the crack grow process induced by thermal loading. Riddle et al. [75] addressed crack damage initiation and propagation in metal laminates. The developed technique is also applicable to electronic and photonic systems. Bae and Krishnaswamy [76] considered "subinterfacial" cracks in bimaterial systems subjected to mechanical and thermal loading. Tee and Zhong [77] applied fracture mechanics techniques to carry out thermomechanical stress modeling for plastic packages during high-temperature reflow soldering. In summary, we would like to point out that fracture mechanics approaches have a significant potential in analytical modeling of thermal stress related phenomena in electronics and photonics. The challenge is to apply general methods of this science to particular engineering problems and to come up with simple and meaningful constitutive relations useful in the engineering practice.

7 Analytical Modeling Versus Finite-Element Analysis

"Say not 'I have found the truth', but rather
'I have found a truth'."
Khalil Gibran, Lebanese Poet and Artist

FEA has become, since the mid1950s, the major resource for computational modeling in engineering, including the area of electronics and photonics (see, for instance, the early work by Lau [78], Glaser [79], and Akay and Tong [80]). Today's powerful and flexible FEA computer programs enable one to obtain, within a reasonable time, a solution to almost any stress-strain-related problem. The FEA software tools (NASTRAN, ANSYS, ABAQUS, etc.) are widely used in applied science and engineering. The amount of publications using FEA to model thermal stress in electronic and photonic systems is enormous. These publications, although might be useful in many engineering applications, seldom add something new to the science and art of analytical modeling, and are beyond the scope of this review. We would like to express, however, some general considerations concerning the interaction of computer-aided (primarily FEA-based) and analytical modeling approaches.

Broad application of computers and FEA computer programs has by no means made analytical solutions unnecessary or even less important, whether exact, approximate, or asymptotic. Simple analytical relationships have invaluable advantages because of the clarity and "compactness" of the obtained information and clear indication on "what affects what and what is responsible for what." These advantages are especially significant when the parameter of interest depends on more than one variable. As to the asymptotic techniques and formulas, analytical modeling can be successful in the cases, in which there are difficulties in the application of computational methods, e.g., in problems containing singularities. Such problems are quite typical in thermal stress analyses.

Even when application of numerical methods encounters no significant difficulties, it is always advisable to investigate the problem analytically before carrying out computer-aided analyses. Such a preliminary investigation helps to reduce computer time and expense, develop the most feasible and effective preprocessing model, and, in many cases, avoid fundamental errors. Those that have a hands-on experience in using FEA know well that it is easy to obtain a solution based on the FEA software, but it might not be that easy to obtain the right solution. It is easy to generate an enormous amount of data using FEA, but the results might be either erroneous or hard to interpret and explain.

Preliminary analytical modeling can be helpful in creating a meaningful and economic preprocessing simulation model. This is particularly true in photonics engineering, where exceptionally high accuracy is required. By changing the mesh and/or the type of the finite-element one can easily deviate from one solution to another by a couple of microns or a split of a degree. Special attention should be paid therefore to make the existing FEA programs accurate enough to be suitable for the evaluation of the tiny thermomechanical displacements in an opto-electronic or a photonic system when a minor offset or an angular misalignment can result in a significant change in the coupling efficiency. Another challenge has to do with the necessity to consider visco-elastic and time-dependent (creep and stress-relaxation) behavior of photonic materials to avoid compromising the long-term functional reliability of the device. Analytical models typically do not encounter such challenges.

It is noteworthy also that FEA was originally developed for structures with complicated geometry and/or with complicated boundary conditions when it might be difficult to apply analytical approaches. Consequently, FEA has to be used in areas of engineering where structures of complex configuration are typical: aerospace, marine, and offshore structures, some complicated civil engineering structures, etc. In contrast, a relatively simple geometry and simple configurations usually characterize electronic and photonic assemblies and structures. Such structures can be easily idealized as beams, flexible rods, circular or rectangular plates, frames, or composite structures of relatively simple geometry lending them to effective analytical modeling.

The application of a FEA computer package is usually perceived as less challenging than analytical modeling. FEA simulations are indeed often rather straightforward and therefore there is a widely spread illusion in the simplicity of the application of the FEA techniques: "As long I push the right button on the computer keyboard, I will get the right answer." The truth of the matter is that no modeling technique, no matter how powerful it might be, could substitute for the in-depth understanding the physics and mechanics of the phenomenon of interest.

Both analytical modeling and FEA simulations have to be applied whenever and wherever possible to obtain preliminary and trustworthy information about the material and structural behavior.

8 Solder Joints

"A formula longer than three inches is most likely wrong."
Unknown Experimental Physicist

Tin-based solder materials were used in radio-engineering and electronics since late 1920s to provide electrical connection. It is only in the late 1970s when these materials (tin-lead eutectics) were considered as joints that can provide also mechanical (physical) support for electronic structures. Solder materials, when subjected to thermal or mechanical loading, exhibit elasto-plastic behavior. They work in the low-cycle fatigue region and their durability is primarily determined by the inelastic (irreversible) strains. These strains are responsible for the accumulated damage during temperature cycling.

Numerous, primarily experimental or FEA based, empirical and numerical models have been developed for the evaluation of thermal stresses in, and prediction of the lifetime of, solder joint interconnections (see, for instance, Refs. [81–107]) subjected to thermo-mechanical loading. The FEA models typically incorporate general phenomenological (semi-empirical) constitutive relations obtained by materials physicists for ductile materials of general nature [108–114]. These models are, of course, extremely important, but they are not necessarily based on the methods of engineering mechanics and mathematical physics, which are the subject of this review.

The studies carried out in the 1990s addressed primarily flip-chip tin-lead solder joint interconnections. The majority of the today's studies concern the prediction of the thermal fatigue life of ball-grid-array (BGA) interconnections and especially lead-free solder joints. The thermally induced stresses and strains in the flip-chip solder joints are caused by the thermal expansion (contraction) mismatch of the chip and the package substrate materials as well as by the temperature gradients because of the difference in temperature between the "hot" chip and the "cold" substrate. In BGA structures the thermally induced stresses and strains are caused by the mismatch of the package structure and the printed circuit board (PCB) (sometimes referred to as "system's substrate").

The suggested phenomenological semi-empirical models are based on the prediction and improvement of the solder material fatigue, which is caused by the accumulated cyclic inelastic strain in the solder material. This strain is due to the temperature fluctuations resulting from the changes in the ambient temperature (temperature cycling) and/or from heat dissipation in the package (power cycling). The (modified) Coffin–Manson model

$$N_f = Af^{-\alpha}\Delta T^{-\beta} \exp\left(-\frac{U}{kT_{\max}}\right)$$

can be used to model crack growth in solder and other metals due to temperature cycling. In the above formula, N_f is the number of cycles to failure, f is the cycling frequency, ΔT is the temperature range during a cycle, $T_{\max}$ is the maximum temperature reached in each cycle, and k is Boltzmann's constant. Typical values for the cycling frequency exponent α and the temperature range exponent β are around $-1/3$ and 2, respectively. Reduction in the cycling frequency reduces the number of cycles to failure. The activation energy U is around 1.25.

In recent years a viscoplastic rate-dependent constitutive model, known as Anand model [112], is often used in combination with the FEA simulation to predict the solder joint reliability. In Anand's model plasticity and creep are unified and described by the same set of flow and evolution relations. Anand's relationships include one flow equation and three evolution equations. The Anand model was applied in Ref. [96] to represent the inelastic deformation behavior for a Pb-rich solder 92.5Pb5Sn2.5Ag used in electronic packaging and surface mount technology. In order to obtain the acquired data for the fitting of the material parameters of this unified model for 92.5Pb5Sn2.5Ag solder, a series of experiments of constant strain rate test and constant load creep test was conducted under isothermal conditions at different temperatures ranging from -65°C to 250°C. A procedure for the determination of material parameters was proposed. Simulations and verifications showed good agreement between the model predictions and the experimental data. In Ref. [97] Anand's model was applied to represent the inelastic deformation behavior of 92.5Pb5Sn2.5Ag solder alloys. After conducting creep tests and constant strain rate tests, the material parameters for the Anand model of the Pb-rich content solder 92.5Pb5Sn2.5Ag were determined from the experimental data using a nonlinear fitting method. The material parameters for 60Sn40Pb, 62Sn36Pb2Ag, and 96.5Sn3.5Ag solders were fitted from the conventional models in literature where plasticity and creep are "artificially" separated. The authors conclude that Anand's viscoplastic constitutive model possesses some advantages over the "separated" model. The Anand model has been applied in FEA simulation of stress/strain responses in solder joints for a chip component, thin quad flat pack, and flip-chip assembly. The simulation results were found to be in good agreement with the available results in literature.

Various (viscoplastic) models for predicting the fatigue lifetime of the solder material were suggested in the past by Solomon [81], Morgan [83], Hatsuda et al. [84], Iannuzzelli et al. [92], and many others. The state-of-the-art in the prediction of the lead-free solder interconnect reliability can be found in the book by Shangguan [103]. The Coffin–Manson model has been applied for the past 2 decades or so by many authors. Gektin et al. [94,95] applied this model to evaluate the fatigue of the solder joint interconnections in flip-chip structures with underfills. Cui [102] carried out accelerated life testing on the basis of the Coffin–Manson model. Modeling of the BGAs and particularly those employed in chip-scale-packages (CSPs) was carried out by numerous investigators (see, for instance, Refs. [98–104]). Fjelstad et al. [99] evaluated CSP for modern electronics, and Ghaffarian [104] addressed the possibility of employing such CSPs for the outer space applications. Lau et al. [101] suggested a thermal fatigue life prediction equation for a wafer level CSP lead-free solder joints.

The ultimate strength of solder joint interconnections is typically measured by shear-off tests. A "twist-off" technique for testing solder joint interconnections was suggested in Ref. [82] and was developed in application to FC and BGA assemblies. It enables one to adequately mimic the actual state of stress in such interconnections.

One effective way to reduce the thermal stresses in solder joints is by employing a flex circuit [85–87]. The developed analytical models can be used to assess the incentive for the application of such circuits as well as the expected stress relief. Juskey and Carson [87] suggested that flex circuits can be used as carriers for the direct chip attachment (DCA) technology. Flex circuitry offers a low-cost and reliable system with a low thermal stress level.

Solder materials and solder joints are as important in photonics, as they are in microelectronics. There are, however, some specific requirements for the photonics solder materials and joints: ability to achieve high alignment, requirement for a low creep, etc. [105]. "Hard" (high-modulus) solder materials (such as, say, gold-tin eutectics) are thought to have better creep characteristics than "soft" (such as, say, silver-tin) solders. It should be pointed out, however, that hard solders can result in significantly higher thermally induced stresses than soft solders. For this reason their ability to withstand creep might not be as good as expected, not to mention the short-term reliability of the material.

Thermally induced stresses and strains in optical fibers soldered into different ferrule materials were modeled in Ref. [89]. Modeling was based on the solution to the axisymmetric theory-of-elasticity problem for an annular composite structure comprised of the metalized silica fiber, the solder ring, and the ferrule. The obtained relationships enable one to design the joint in such a way that the solder ring is subjected to relatively low compressive stresses. It has been shown that neither low-expansion ferrules nor high-expansion ones might be suitable for a particular solder material and that materials with moderate coefficients of expansion might be more preferable. In any event, it is imperative that analytical stress modeling is used to select the most appropriate geometries and mechanical properties of the solder materials for a particular material of the ferrule or vice versa.

Solders are often used also as continuous attachment layers in electronic and photonics assemblies. In general, as long as all the materials are considered linearly elastic, the models developed for adhesively bonded joints can be applied to soldered assemblies as well. However, elevated stresses at the ends of soldered assemblies can lead to plastic deformations of the solder material. This problem has become increasingly important in connection of using indium as a suitable bonding material of the quantum wells of GaAs lasers to metal substrates (submounts). In this connection, the model [18] was generalized in Ref. [106] for the situation when the peripheral portions of the solder material with a low-yield-stress exhibit ideal plasticity. Clearly, the actual stress condition is between the two extreme situations: ideal elasticity addressed in Ref. [18] and ideal plasticity (above the yield point) considered in Ref. [106]. Note that the models suggested in Refs. [19,58] suggest that the diagrams for the interfacial shearing and peeling stresses get "truncated" on the level of the yield-stress for the bonding material. It has been demonstrated, however [106], that this approach is extremely nonconservative, i.e., leads to a significant underestimation of the lengths of the plastic zones. The model [106] suggests a transcendental equation for the length of the plastic zones. This equation considers the redistribution of the stresses due to the ideal plasticity of the bonding material.

9 "Global" and "Local" Mismatch and Assemblies Bonded at the Ends

"If my theory is in conflict with the experiment, I pity the experiment."
Georg Wilhelm Friedrich Hegel, German Philosopher

When the adhesive layer is inhomogeneous, or when the components are just partially bonded or soldered to each other, both "global" and "local" mismatch loadings take place [115–118]. "Local" thermal expansion (contraction) mismatch loading is due to the mismatch of dissimilar materials within the bonded or soldered region, while the "global" mismatch loading is caused by the mismatch of the adherends in the unbonded region. Thermally induced stresses due to the "global" mismatch can be modeled, as far as the stress in the bonding material is concerned, as the structural response to an equivalent external "mechanical" (rather than thermal) loading.

Examples of structures experiencing both types of stresses are solder joint interconnections, optical glass fiber interconnects adhesively bonded or soldered at their ends into a ferrule or a capillary, optical glass fiber in a micromachined (MEMS) optical switch packaged into a dual-in-line package, etc.

The interaction of the thermally induced interfacial shearing stresses caused by the "global" and "local" mismatches in a typical bimaterial assembly adhesively bonded or soldered at the ends can be qualitatively summarized as follows.

- Interfacial shearing stresses caused by the "local" mismatch are antisymmetric with respect to the mid-cross-section of the bonded area: these stresses are equal in magnitude and opposite in directions (signs).
- "Local" shearing stresses that concentrate at the ends of the bonded area in sufficiently long bonded joints and/or in joints with stiff interfaces (thin and high-modulus adhesive layer) are next to zero in the midportion of the bonded area.
- For short and/or compliant bonded areas, the "local" shearing stresses are more or less linearly distributed over the length of the bonded area, and their maxima at the assembly ends can be significantly lower than the maximum stresses in long and/or stiff bonded areas.
- Shearing stresses caused by the "global" mismatch act in the same direction over the entire length of the bonded joint. This direction is such that in the inner portions of the joints (i.e., in the portions located closer to the mid-cross-section of the unbonded region, which is also the mid-cross-section of the assembly as a whole), the total interfacial stress should be computed as the difference between the "local" and the "global" stress. In other words, the interaction of the "local" and the "global" stresses at the inner portion of the joint is always favorable, as far as the induced stresses are concerned, i.e., leads to lower total stresses. In the outer portions of the bonded joints, however, the total stress (strain) should be computed as the sum of the "local" and the "global stress."
- In the case of small-size joints and/or joints with compliant interfaces, the total stress at the outer end of the joint can be considerably larger than each of the stress categories taken separately. Since both the "local" and the "global" stresses in short and/or compliant joints can be very low compared with the stresses in long and/or stiff assemblies, the total stress can be low as well, despite the fact that, for the outer (peripheral) portions of the bonded joints, this stress is obtained as a sum of the "local" and the "global" stresses. It is noteworthy, however, that enough "real estate" is always necessary to provide good adhesion, and therefore small-size joints with compliant interfaces might not be advisable despite the possible low stress level.
- In the case of long and/or stiff joints, the "global" stresses concentrate at the inner edges of the joints and rapidly decrease with an increase in the distance of the given cross section from these edges. In such a situation, as has been indicated above, the interaction of the "local" and "global" stresses is always favorable: at the inner edge of the assembly, this interaction results in the total stress, obtained as a difference between the "local" and the "global" stress, while, at the outer edge of the assembly, "local" stress only exists.
- For sufficiently long and/or stiff bonded joints, the magnitude of the "global" stress at the inner end is equal to the magnitude of the maximum "local" stress so that the total shearing stress is simply zero. In other words, the state of stress in such a joint is the same for the joint with a continuous bonding layer and for an assembly adhesively bonded at the ends, provided that in the latter case the joint is long enough.

The interaction of the "local" and the "global" stresses, with consideration of the effect of the coefficient of thermal expansion (contraction) of the epoxy material itself, was studied in Ref. [118] in application to a glass fiber interconnect whose ends are epoxy bonded into capillaries. The necessity of taking into account the CTE of the adhesive material was due to the fact that the cross-sectional area of the adhesive ring was considerably larger than the cross-sectional area of the glass fiber. For this reason the longitudinal compliance of the adhesive ring was comparable with the compliance of the fiber itself and could not be neglected.

Understanding the interaction of the "global" and "local" stresses is particularly important in connection with the electronic and photonic assemblies bonded at the ends. In some microelectronic assemblies of the flip-chip type the solder joint stand-off is so small that it is next to impossible to bring in the underfill material underneath the chip, especially if the size of the chip is large. On the other hand, there might be no need for that since the underfill material, as a structural element, works only at its peripheral portions. Modeling of the mechanical behavior of such an assembly is crucial in order to establish the adequate width of the bonding layer: this width should be large enough to provide sufficient bonding (adhesive) strength of the assembly, but does not have to be larger than necessary. The stresses in such an assembly will not be higher than in an assembly with a continuous underfill (bonding layer).

10 Assemblies With Low-Modulus Adhesive Layer at the Ends

"All the general theories stem from examination of specific problems."
Richard Courant, German Mathematician

Interfacial shearing and peeling stresses in adhesively bonded or soldered assemblies concentrate at the assembly ends. There is an incentive therefore to use a low-modulus bonding material at the ends for lower interfacial stresses. In other words, there is no need to employ a low-modulus material throughout the interface: it is sufficient to use it only at the assembly ends [119–122]. This could be done in addition to, or instead of, slanting the edges of the assembly components [120]. The latter structural change increases the thickness of the adhesive layer at the assembly ends only, where such an increase could make a difference. The stresses at the ends of polymer-coated optical fibers can be reduced by using a low-modulus coating at the fiber ends [121,122].

The mechanical behavior of electronic and photonic structures with a low-modulus adhesive layer at the ends is, in a sense, opposite to the situation that takes place in an assembly adhesively bonded at the ends. Indeed, in an assembly with a low-modulus adhesive/coating at the end, it is the midportion of the assembly that is characterized by relatively high Young's modulus of the adhesive (coating), while in the case of an assembly bonded at the ends, it is the assembly midportion that is characterized by "low" (actually, zero) Young's modulus of the "attachment." Both situations have, of course, their pros and cons, and their areas of applications in electronic and photonic engineering. It is advisable to model the interfacial thermal stresses in assemblies with inhomogeneous (e.g., piecewise-continuous) bonding layers for lower interfacial stresses. Such layers should employ bonding "pieces" with reduced Young's moduli and perhaps varying lengths as well along the interface.

11 Thermally Matched Assemblies

"Nothing is impossible. It is often merely for an excuse that we say that things are impossible."
François de La Rochefoucauld, French Philosopher

There is an obvious incentive to use thermally matched materials in electronic and photonic assemblies [123–128]. Such an assembly was employed particularly in the Bell Labs Si-on-Si flip-chip FC design (Fig. 6) [124], in a ceramic CERDIP/CERQUAD package [125], and in the advanced low-cost holographic memory storage assembly [126–128], where a highly compliant (thick and low-modulus) adhesive of the silicone gel type was used as a memory storing medium.

There is a difference in the mechanical behavior of assemblies with an appreciable CTE mismatch of the adherends and thermally matched assemblies, particularly those with identical adherends. While in assemblies with an appreciable thermal mismatch of the adherends, the CTE of the adhesive material (as long as this material is thin and has a low Young modulus) does not affect the mechanical behavior of the assembly, in assemblies with identical adherends the mismatch between the adhesive and the adherend materials the CTE of the adhesive is certainly important. In addition, the mechanical behavior and reliability of the adhesive material are quite different. In "conventional" assemblies with mismatched adherends and thin and low-modulus adhesives, the state of stress and strain of the adhesive layer is determined primarily by the interfacial shearing and peeling stresses, while in the case of matched assemblies (identical adherends) the adhesive layer experiences both elevated interfacial stresses and normal stresses acting in its cross sections. A thin layer of the adhesive material in assemblies with identical adherends behaves, to a certain extent, similar to a thin film fabricated on a thick substrate.

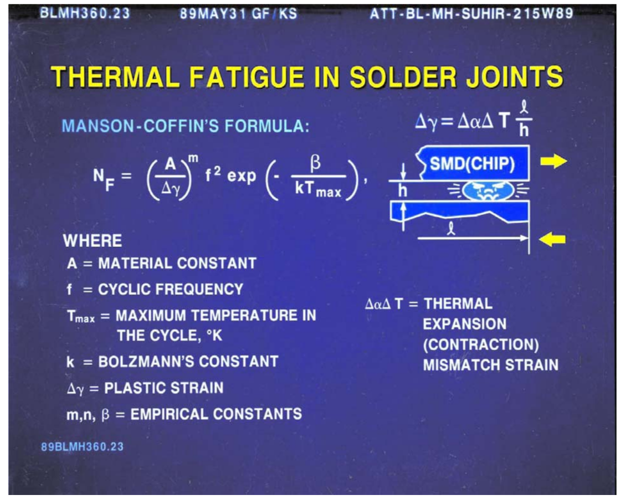

Fig. 5 Low-cycle thermal fatigue in solder joints employed in thermally mismatched assemblies

In the analytical model developed in Ref. [123] an actual solder joint in a Si-on-Si flip-chip design (Figs. 5 and 6) was substituted by a short ("finite") circular cylinder subjected to the axisymmetric shear loading applied to its plane ends (Fig. 7). Such a loading reflects the situation of a local mismatch during temperature cycling or reflow soldering conditions, i.e., the situation when no temperature gradients take place. The solution was obtained on the basis of a theory-of-elasticity approach using modified Bessel functions. The analytical predictions were in good agreement with FEA data. One of the numerous FEA models generated in the project is shown in Fig. 8. It has been demonstrated particularly that although the external thermal loading was due to the shearing deformations of the "butt" planes, the maximum stresses and strains were the normal ones acting in the axial direction, i.e., the stresses and strains of the peeling nature.

The case of identical ceramic adherends was considered also in connection with choosing an adequate coefficient of thermal expansion for a solder (seal) glass in a ceramic package design [125]. It has been found that the observed numerous failures in the initial design of the ceramic/seal-glass assembly were due to the higher CTE of the glass than of the ceramic material. This led to the tensile stresses in the glass layer at low-temperature conditions and resulted in its brittle fracture. The situation was improved dramatically when the seal-glass material with a low CTE (compared with the ceramic material) was selected. The package manufactured in accordance with the developed recommendations exhibited no failures. As far as modeling was concerned, it was

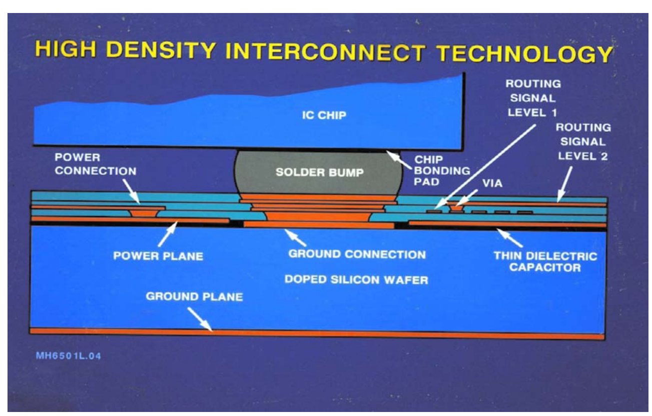

Fig. 6 Silicon-on-silicon high density interconnect technology

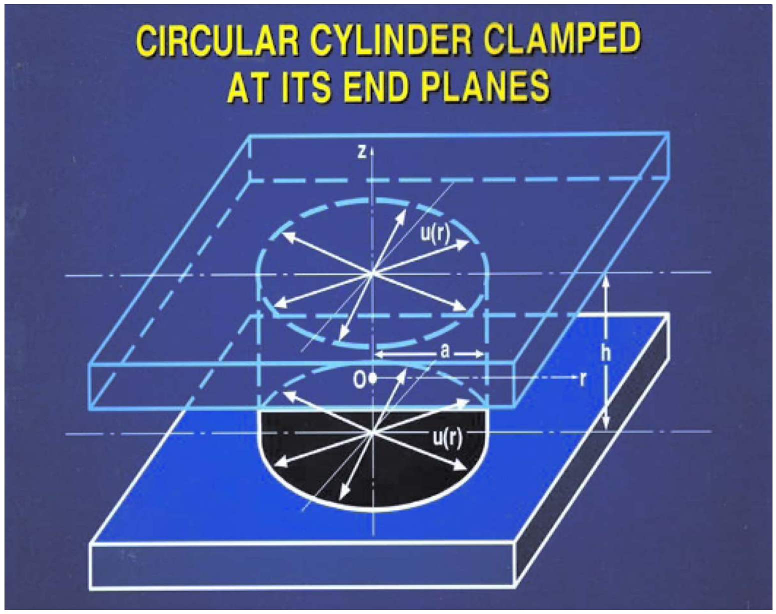

Fig. 7 A solder joint in a thermally matched Si-on-Si assembly can be modeled as a short circular cylinder clamped at its end planes

determined that the best result could be achieved by using a probabilistic approach, in which the CTEs of the solder glass and the ceramic materials were treated as random variables.

The probabilistic physical design of the improved structure was based on the requirement that the high probability that the normal stress in the cross sections of the seal glass is always negative (i.e., the glass material is always in compression). On the other hand, this compression should be low enough so that the generated interfacial stresses at the glass/ceramic interface do not exceed a certain allowable level. Based on the performed analysis, it was concluded that in order to successfully apply a probabilistic approach (see, for instance, Ref. [125]) in the designs of the type in question, manufacturers (like AT&T in that case) should require that material vendors provide information concerning not only the nominal (say, mean or most likely) values of the material characteristics (CTEs), but also the standard deviations (variances) of these characteristics.

In this connection we would like to point out that it is always advisable to carry out sensitivity analyses of the thermal stresses in order to establish in which cases one can get away with a deterministic model based on a more or less tentative mechanical characteristics of the employed materials, and when a more thorough evaluation of these characteristics is necessary, so that a probabilistic analysis and a physical design, based on such an analysis (probabilistic physical design), should be employed.

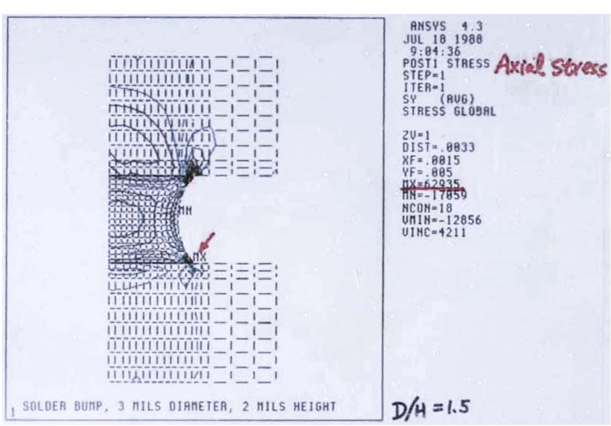

Fig. 8 Finite-element model for the joint shown in Fig. 7

Several analytical thermoelastic models [126–128] were developed for the prediction of the mechanical behavior of the bonding material in adhesively bonded assemblies with identical nondeformable adherends of a rectangular or circular configuration. The analyses were carried out in application to assemblies that were intended for advanced holographic memory devices. It has been shown, particularly, that the interfacial compliance κ of the bonding layer, in the case of sufficiently large and thin assemblies with thermally matched adherends, is half the magnitude of the interfacial compliance in the case of assemblies with thermally mismatched adherends. This circumstance is due to the fact that the interfacial shearing stresses acting on the bonding material in thermally mismatched assemblies are directed, at the given cross section of the assembly, in opposite directions, while, in the case of the thermally matched assemblies, these stresses act in the same direction. For this reason the stresses of the same magnitude result in significantly lower angular (shearing) strains. It has also been shown that the elevated interfacial shearing stresses are somewhat higher for a circular assembly with identical adherends than for a rectangular one. These stresses also occupy a narrower zone around the assembly edge.

An inhomogeneous adhesive layer, which is important for the considered application, was examined in Refs. [88,89]. Ref. [88] addresses a situation when Young's moduli of the bonding layer in the midportion of the assembly and at its periphery are different. The objective of the analysis was to find out how wide the peripheral portion ("ring") should be so that the thermal strains at the inner boundary of this portion would be so small that this boundary would not be distorted, i.e., will remain plane despite the possible change in temperature. The fulfillment of such a requirement is important from the standpoint of the optical performance of the bonding (memory carrying) material.

Reference [89] generalizes the solution obtained in Ref. [88] for the situation of a "piecewise-continuous" bonding layer. The ultimate objective of the analysis was to establish the conditions at which the requirement for the undistorted boundaries of the inner pieces of the adhesive is fulfilled. The obtained governing equations are of the same type as the well-known equations of the "theorem of three moments" in the theory of beams lying on discrete rigid supports (see, for instance, Ref. [25]). The left parts of the equations are the unknown thermally induced forces at the boundaries of the adjacent pieces of the bonding material, and the right parts, "the loading terms," are due to the CTE mismatches of these materials with the substrate materials and with each other.

12 Thin Films

"Mathematicians are like the French: when you talk to them they translate your words in their language, and at once you cease to understand them."

Johann Wolfgang Goethe, German Poet

Typical thermal stress failures in thin films fabricated on thick substrates are interfacial delaminations (including delamination buckling), and film cracking and blistering. Numerous investigators (see, for instance, Refs. [129–141]) analyzed thermal stresses in thin film systems intended for different applications. Based on the obtained results, practical recommendations for the physical design of a reliable thin film structure have been formulated. Based on analytical stress modeling it has been found that

- the thermal stress in the given film layer of a multilayer film structure is due to the thermal expansion mismatch of this layer with the substrate, and not with the adjacent film layers [95];
- the edge stresses in the film are affected by the edge configuration [100,101]: circular assemblies are somewhat "stiffer" than the rectangular ones, i.e., result in higher stresses that concentrate at a more narrow peripheral portion (ring) of the assembly;
- stress in a thin film, which does not experience bending stresses, is not affected by the assembly bow, while the assembly bow and the stresses in the substrate are strongly affected by the stresses in the film.

The effect of the lattice mismatch of semiconductor materials during crystal growth of thin germanium (Ge) films on a thick silicon (Si) substrate was addressed, along with the effect of thermal mismatch, by Luryi and Suhir [56]. It has been shown that by using a "towerlike" surface of the substrate (such a surface can be achieved by high-resolution lithography, by employment of porous silicon, etc.) one can indeed grow dislocation free semiconductor films.

13 Polymeric Materials and Plastic Packages of IC Devices

"In a long run we are all dead."

John Maynard Keynes, British Economist

Polymeric materials are widely used in electronic and photonic engineering [142–153]. Examples are plastic packages of IC devices, adhesives, various enclosures and plastic parts, polymeric coatings of optical silica fibers, and even polymeric light-guides. There are numerous and rapidly growing opportunities for the application of polymers for diverse functions in the nanotechnology field. Polymeric materials are inexpensive and lend themselves easily to processing and mass production techniques. The reliability of these materials, however, is usually not as high as the reliability of inorganic materials and is often insufficient for particular applications, thereby limiting the area of the technical use of polymers. There exists a crucial necessity therefore for the advancement of the experimental and theoretical methods, techniques, and approaches, aimed at the prediction and improvement of the short-/long-term performance of polymeric materials for electronic and photonic applications.

Polymeric materials are characterized, as a rule, by high CTEs, and their mechanical (physical) behavior and performance are affected by the level of the glass-transition temperature: Young's modulus drops by an order of magnitude or more, and the CTE increases two to three times, when the polymeric material undergoes glass-transition state. In addition, the mechanical properties of polymeric materials are temperature dependent. These circumstances should be considered in the thermal stress modeling for these materials.

Let us indicate just several models of thermal stress in polymeric materials and plastic packages of IC devices. Suhir [142] evaluated the elastic stability of an epoxy cap in a flip-chip package design. van Doorselaer and deZeeuw [143] modeled the delamination problem in plastic packages of IC devices. Pendse and Demmin [144] applied FEA to establish the level of thermal stresses in such devices. Although recent improvements in the mechanical properties of molding compounds, plastic package designs, and manufacturing technologies have resulted in substantial increase in the reliability of plastic packages, there still exists one major industry-wide concern associated with these packages—their moisture-induced failures ("popcorn" cracking) [146–148]. Such failures typically occur during surface mounting the packages onto PCBs using high-temperature (220–280°C) reflow soldering. Popcorn cracking is usually attributed to the elevated pressure of the water vapor generated due to a sudden evaporation of the absorbed moisture. It is believed, however, that thermal stresses also play an important role, both directly, due to their interaction with the mechanical vapor-pressure-induced stresses in the underchip portion of the molding compound, and indirectly, by triggering the initiation and facilitating the propagation of the interfacial delaminations.

It has been suggested [148] that constitutive equations, obtained as a generalization of von Karman's equations for large deflections of plates, can be used as a suitable analytical stress model for the prediction and prevention of structural failures in moisture-sensitive plastic packages. Such a generalization accounts for the combined action of the lateral pressure, caused by the generated water vapor, and the thermally induced loading. The developed model can be used for the selection of the low stress molding compounds, for comparing different package design from the standpoint of their propensity to popcorn cracking, and for the development of "figures-of-merit" [146]. Such "figures" enable one to separate packages that need to be "baked" and "bagged" from those that do not. The loading on the underchip portion of the molding compound is due to both the temperature gradients and the thermal expansion (contraction) mismatch of the dissimilar materials in the package. Since the CTE and Young's modulus of the molding compound are temperature dependent, the constitutive equations account for this dependence.

The developed equations were applied to evaluation of the mechanical behavior of the delaminated underchip layer of the molding compound. This layer was treated as a thin rectangular plate clamped at the support contour. It has been shown, in particular, that from the standpoint of structural analysis, the distinction between "thick" and "thin" packages should be attributed primarily to the level of the in-plane ("membrane") normal stresses in the underchip portion of the compound: in thick packages this portion exhibits bending only, while in thin packages it is subjected to both bending and in-plane loading. The obtained data, which are in good agreement with experimental observations and FEA data, have indicated that the geometric characteristics of the package (the underchip layer thickness, chip and paddle size, etc.) have a strong effect on the package propensity to failure.

14 Thermal Stress Induced Bow and Bow-Free Assemblies

"By asking for the impossible obtain the best possible."

Italian Proverb

Significant thermal stress induced bow can prevent further processing of the BGA packages or of thin (TSOP and CSP) plastic packages of IC devices [154–159], can lead to cracking of ceramic substrates in thin overmolded packages [155,156], or can have another adverse effect on the design and processing of plastic IC packages. Analytical models for the prediction of thermal stress induced bow of plastic packages of IC devices were suggested in Ref. [154] in application to thin small-outline packages (TSOPs). The bow of such packages is due to the thermal contraction mismatch of the lead-frame and polymeric materials as well as to the temperature gradients arising when a newly fabricated plastic package is placed on a cold table for rapid cooling.

Ceramic substrate cracking has been observed in overmolded packages of IC devices [155,156]. It has been shown that employment of additional (surrogate) layers can dramatically improve the situation. Two major techniques/approaches had been considered: application of a thin surrogate layer of a high-expansion, high-modulus, and high-strength layer of a polymeric material fabricated at the opposite side of the ceramic substrate [155] and application of a thin surrogate layer of a negative-expansion ceramics over the plastic material [156].

There is an obvious incentive for the use of bow-free (temperature change insensitive) assemblies in electronics and especially in photonics. It has been shown [157–159], based on analytical stress modeling, that this can be achieved if a thick enough bonding layer is introduced to produce an appreciable axial (in-plane) force. This force is necessary to create a bending moment that would be able to equilibrate the thermally induced moment produced by the dissimilar adherends.

A bimaterial assembly (i.e., an assembly with a very thin and/or a very low-modulus bonding layer) is statically determinate and cannot be made bow-free. The thermally induced forces acting in the components of a bimaterial assembly are equal in magnitude and opposite in sign, and create a bending moment that can be equilibrated by the elastic moment only. This inevitably leads to nonzero deflections, whether large or small. To be bow-free, a multimaterial assembly should be made statically indeterminate. It should contain, therefore, at least three dissimilar materials with large enough flexural rigidities so that the resulting bending moment, caused by the induced forces in all the three materials, is zero.

A sufficiently large axial force in the bonding material can be created by one or by a combination of two or more of the following measures:

- by using a bonding material with a high elastic modulus;
- by using a bonding material with a significant thermal mismatch with the adherends;
- by using a bonding material with a high curing temperature, and/or
- by making the bonding material thick.

It is only the last measure, however, that, while resulting in a desirable elevated thermally induced force in the bonding material, does not necessarily lead to an elevated axial stress in it. Computations based on the developed analytical models have indicated that the thick bonding layer in a bow-free assembly can still be made thin enough (not thicker than about 4 mils or so) to do the job, provided that the material and/or the thickness of at least one of the adherends is adequately chosen. It goes without saying that an initially bow-free assembly will remain bow-free if the employed materials do not exhibit any stress-relaxation or other time-dependent phenomena that could lead to the redistribution of the stresses required for the bow-free state. This might be challenging though since bow-free assembly might experience rather high thermal stresses.

15 Optical Fibers and Other Photonic Structures

"Mathematics to an engineer is a means, a tool, which is similar to a caliper, chisels, hammer, file to a craftsman, or a yard stick, hatchet and a saw to a carpenter."

Alexei Krylov,
Russian Naval Architect and Applied Mathematician

Various problems of thermal stress modeling in bare and coated optical silica fibers were addressed in numerous investigations. Some of them [122,160–193] are briefly described below.

Low-temperature microbending [176–182] can result in substantial added transmission losses in dual-coated optical fibers. This phenomenon is due to the loss of elastic stability of the silica optical fiber within the low-modulus primary coating in a dual-coating system. The compressive axial force is caused by the thermal contracting mismatch of the high CTE secondary coating and the low CTE silica fiber. Based on the developed analytical stress models, it has been shown that the initial curvatures can play an important role in the low-temperature behavior of a silica fiber and that, from the standpoint of the possible fiber buckling, certain curvature lengths are less favorable than the others. This is because a dual-coated fiber supported by an elastic foundation (which is provided by the low-modulus primary coating) behaves, with respect to the initial curvatures, like a narrow-band filter that enhances the initial curvatures, which are close to the post-buckling configuration of the fiber, and suppresses all the other curvatures. It has also been shown that the spring constant of the elastic foundation provided by the primary coating has a significant effect on the buckling conditions and that, in the case of thick and not very high-modulus secondary coatings, the compliance of both coating layers should be considered when evaluating the spring constant. For thin and high-modulus secondary coatings, however, only the primary coating material could be considered. The developed models enable one to predict the mechanical behavior of the dual-coated optical fiber at low-temperature conditions and to design the coating system so that the elastic stability of the fiber is not compromised.

Application of the mechanical approach to the evaluation of low-temperature added transmission losses enables one, based on the developed analytical stress model, to evaluate the threshold of the low-temperature added transmission losses from purely mechanical calculations, without resorting to optical evaluations or measurements [164]. The model (confirmed by such measurements) presumes that the threshold of the elevated added transmission losses coincides with the threshold of the elevated thermally induced stresses applied by the polymeric coating (jacket) to the silica fiber. Such a "presumption" was actually based on the experimental data.

The effect of axial loading on polymer-coated optical fibers has been addressed in Refs. [183–190]. Such a loading can be either mechanical or can be due to the thermal expansion (contraction) mismatch of the coated optical fiber and its enclosure. Quite often a coated optical fiber experiences a combination of mechanical bending and mechanical or thermal axial loading. The engineering theory of single-span beams subjected to bending can be applied to evaluate the induced stresses in optical fibers. The developed models address bending and axial stresses in optical fiber interconnects experiencing end offset, angular misalignment of the end cross sections, and the effects of thermally induced compressive or tensile loading because of the thermal expansion (contraction) mismatch of the silica material with the material of the enclosure. In those cases when low buckling stresses are a problem, thicker polymer coatings can be used to improve the elastic stability of a polymer-coated fiber [185]. It has been shown particularly that as far as the thermal stresses in the coating (metallization) are concerned, low-modulus polymer coatings have significant advantages over high-modulus metallizations, and should be preferred in actual engineering designs despite of their sensitivity to moisture. Shiue [165,173,174,178,179,181,182,186] developed several analytical stress models for the evaluation of the mechanical (physical) behavior of double-coated and jacketed (single-coated) optical fibers at low-temperature conditions. King and Aloisio [175], using the plane strain approximation of the 2D theory of elasticity, obtained an analytical solution for the evaluation of the possible delamination of the polymer coatings from a silica optical fiber. Suhir and Vuillamin [166] demonstrated, based on the developed analytical and FEA models, that the gradient in the distribution of the CTE along one of the diameters of a glass fiber cross section can be responsible for the undesirable "curling" phenomenon that often occurs during drawing of optical silica fibers. Suhir [191] developed analytical models for the evaluating thermal stresses and strains in fused biconical taper (FBT) couplers.

An effective method for thermostatic compensation of temperature-sensitive devices was suggested in Ref. [168] for application to Bragg gratings. It has been shown that there is no need to use, for particular applications, mechanically vulnerable ceramic materials with a negative CTE: regular and more mechanically reliable materials can be successfully used for the objective in question.

Analytical models for the prediction of the critical force in a dual-coated optical glass fiber subjected to the combined action of the mechanical and thermal loading enable one to evaluate the elastic stability of dual-coated optical fiber interconnects in optical fiber arrays used in termination structures [189,190]. The models are based on the obtained solution for a cantilever beam of finite length lying on a continuous elastic foundation (provided by the primary coating) and subjected to a thermally induced and/or an external compressive force. It has been shown particularly that the critical force for a cantilever beam lying on a continuous elastic foundation is only half of the value that corresponds to the case when the end, at which the compressive force is applied, is not a free one. Based on the obtained solutions, a recommendation for the fiber design with the same critical force in its coated and stripped-off portions was suggested.

Thermal stress can certainly cause material reliability problems in laser chips, but it can result also in spectral broadening and "smile" (near-field nonlinearity) in laser arrays. "Smile" (a slight bend of the horizontal line connecting the emitters) is a potentially disturbing property of diode bars. "Smile" errors can have detrimental effects on the ability to focus beams from diode bars. Liu et al. [192,193] studied the thermal stress effects in single emitter lasers and laser arrays. They found particularly that thermal stress gradients in the individual emitters across the width of the array can lead to undesirable spectral broadening in laser arrays.

16 Probabilistic Approach

"If a man will begin with certainties, he will end with doubts; but if he will be content to begin with doubts, he shall end in certainties."
Francis Bacon, English Philosopher and Statesman

Probabilistic models might be useful and even inevitable in situations where the "fluctuations" from the mean values are significant and when the variability, change, and uncertainty play a vital role [194–196]. In the most situations the structure will likely fail if these uncertainties are ignored. So far, probabilistic (statistical) models are used in high-technology engineering primarily for the design and analyses of experiments. They are seldom used as a physical design tool. In this connection we would like to emphasize that wide and consistent use of probabilistic models would not only enable one to establish the scope and the limits of the application of deterministic models but can provide a solid basis for a well-substantiated and goal-oriented accumulation, and effective utilization of empirical data.

Probabilistic models enable one to quantitatively assess the degree of uncertainty in various factors, which determine the performance of a product. Then a reliability engineer can design a product with a predictable and low probability of failure. A good illustration to these statements is the success of the design described in Ref. [125], where probabilistic analytical thermal stress modeling was applied to analyze, design and manufacture a viable and reliable ceramic package of an IC device. Several other examples can be found in Ref. [195]. To carry out probabilistic analyses one should know, as has been indicated above, not only the mean values of the materials properties but the standard deviations of these properties as well. In many cases the probabilistic characteristics of the thermal loading (such as, say, the external thermal strain $\Delta\alpha\Delta T$) should also be either known or at least assumed for carrying out an appropriate sensitivity analysis.

17 Design Recommendations for Reduced Thermal Stress in Bonded Assemblies

"Truth is rarely pure and never simple."
Oscar Wilde, "The Importance of Being Earnest"

Based on the modeling of thermal stresses in typical adhesively bonded or soldered assemblies, i.e., in assemblies with appreciable CTE mismatch of the adherends and a homogeneous adhesive or solder layer, the following general recommendations, aimed at the improvement of their ultimate and fatigue strength, can be made:

- Equalize the in-plane and bending stiffness of the adherends, and use identical adherends, if possible;
- Use as high an adherend in-plane stiffness as possible;
- Use low-modulus and thick adhesives, having in mind, however, that if an adhesive layer is thick enough (say, 2–3 mils or so in a typical adhesively bonded or soldered joint in electronics or photonics), the further increase in its thickness does not lead to an appreciable reduction in the interfacial stresses);
- As an alternative in using a low-modulus adhesive throughout the joint, use such an adhesive, for lower interfacial stresses, only at the ends of the joint, i.e., in the region of high interfacial stresses, while a higher-modulus adhesive is used, for better adhesion and heat transfer, in the midportion of the assembly;
- Vary, if possible, the adherend thickness along the assembly in a proper way and/or slant the adherend edges, if possible, for a thicker adhesive layer at the assembly ends;
- Keep the stresses within the elastic range, if possible; with this in mind, lead-free solder joint interconnections, although experience higher stresses and require higher soldering temperatures, might exhibit longer fatigue life than tin-lead solders;
- Minimize peeling (in the case of multimaterial and thin film structures) and axial (in the case of solder joints) stresses and strains: It is these stresses and strains that are primarily responsible for the fatigue lifetime of the bonding materials. Consider using, in soldered assemblies, solders with low-yield stress for lower peeling stresses in the assembly.

18 Nanosystems

"It's hard to think of an industry that won't be touched by nano-tech."
Steve Jurvetson, "Mr. Nanotech," Stanford Business School, Forbes Magazine, June 23, 2003

It has been recently demonstrated [197–207] that a newly developed nanoparticle material (NPM) can make a substantial difference in the state-of-the-art of coated optical fibers: This material possesses all the merits of the polymer-coated and metalized optical fibers without having their drawbacks. In general, it would not be an exaggeration to state that nanothermomechanical stress modeling will develop in the near future into a separate important area of mechanical and nanoengineering. We will indicate just several newly published papers related to this area and containing analytical models of thermal stresses.

The model developed in Ref. [189] can be applied not only to dual-coated fibers but also to nanofibers embedded into low-modulus elastic media. In this case the model can be used to find the largest length of such a fiber (or a nanotube) that will remain elastically stable despite the thermally induced compression from the medium. Several analytical stress models have been developed [208–215] for the evaluation of the mechanical behavior of carbon-nanotubes (CNTs) embedded into low-modulus elastic medium and subjected to mechanical to thermal radial ("hoop") stresses and axial compression. The considered CNT arrays are intended for the application in the advanced nanotechnology based heat spreaders.

Substantial relief in the interfacial thermally induced stresses can be expected if the newly developed highly compliant nanomaterial is used as a thermal interface material (TIM) [215]. The developed analytical models enable one to assess the advantages due to the application of such a material. Computations based on these models indicate that the thermally induced stresses can be reduced by two orders of magnitude compared to the stresses acting in the existing devices.

Several analytical predictive models for the evaluation of thermally induced and mechanical stresses in CNT/carbon-nanofiber (CNF) arrays were developed by Zhang et al. [208–212] in application to nanosystems intended for heat transfer in high-power IC devices.

19 Conclusion

"Life is the art of drawing sufficient conclusions from insufficient premises."
Samuel Butler, "The Way of All Flesh"

Modeling is an effective and indispensable tool for the prediction of stresses arising in electronics and photonics materials, structures, packages, and systems subjected to thermal loading. Analytical modeling should be used, whenever possible, together with finite-element modeling, in any significant effort aimed at the analysis and rational physical design of a viable, reliable, and cost-effective electronic, opto-electronic, or photonic system.

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