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Coupled Thermal/Structural Analyses of Laser Powered Glass Sealing Methods for Fiber Optic and Flat Panel Display Applications

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ABSTRACT

Glasses are used extensively by the electronics industry for packaging and in components. Because glasses have such low fracture toughness, glass components must maintain low tensile stresses to avoid cracking and ensure product stability. Modeling is a key tool for developing designs with low tensile stresses. Thermoelastic analyses are ideal for modeling slow, oven controlled processes where the temperature varies uniformly. Many processing environments, however, involve rapid heating and cooling cycles that produce nonhomogeneous temperature fields causing the volume and stresses in the glass to relax at different rates. This structural relaxation is an important nonlinear material behavior that gives rise to a point-to-point variability in "effective" properties of the material. To accurately model such stresses, a thermal analysis must be coupled to a structural analysis that employs a viscoelastic model of glass.

Laser sealing of glasses is an example of a process where thermal history is an important factor in determining the residual stress state. Recent needs to consider laser sealing methods for fiber optic connectors and flat panel displays have spurred the development of coupled, three-dimensional thermal and structural finite element codes. Analyses of the temperatures and stresses generated in a flat panel display during a laser sealing operation are presented, and the idiosyncrasies and importance of modeling coupled thermal/structural phenomena are discussed.

INTRODUCTION

The electronics industry has long embraced the use of glasses in manufacturing a variety of electronic components. Glasses are ideal for making hermetic seals in products which require electrical penetrations and connections to be made to isolated environments. Actuators, batteries, connectors, switches, and detonators are just a few examples of electronic components where glass-to-metal seals are important. The growth of the flat panel display industry also has spawned a variety of sealing issues including interests in novel sealing methods that have the potential for cost savings through automation and higher production rates.

A common method for making glass-to-metal seals in connectors is to assemble glass preforms according to the proposed design lay-up and then to heat the entire assembly to the softening temperature of the glass. At these high temperatures, the glass flows to seal interfaces and the component solidifies during subsequent cool-down. Although sealing methods vary, oven operations are commonly used for their simplicity and ability to maintain fairly uniform temperatures under slow cooling rates. The cooling rate is important because thermal stresses are generated by the disparity in thermal strains created by thermal gradients and by the differences in the thermal expansion coefficients among the sealed materials. Because glasses have such a low fracture toughness, tensile stresses must remain low to avoid cracking and preserve hermeticity.

If heating and cooling rates are sufficiently slow to produce spatially uniform temperatures, then thermal stress analyses can be performed elastically. The detailed temperature/time dependence in the physical properties of the glass is overlooked by employing room temperature mechanical properties and a "temperature set point" (i.e., temperature at which liquid/solid transition is assumed to occur). Component stresses are then only attributable to the mismatch in thermal strains incurred among constituent materials during cooling after the glass has "solidified" at the set point. Moreover, elastic results are independent of the process by which the mismatch in thermal strains is generated.

When cooling is nonuniform or processing behavior is important, analyses become much more difficult. Thermal effects must be accurately modeled, and stress computations must include the time/temperature dependent changes in both volume and stress relaxation, which are strong functions of thermal history. In general, this requires a specialized viscoelastic model of glass, a good understanding of the relevant material properties and thermal boundary conditions defining the process, and a means of coupling three dimensional thermal and structural finite element codes.

GLASS MATERIAL BEHAVIOR

By definition, a glass has a noncrystalline structure and behaves as a viscous liquid at temperatures above glass transition [1]. During cooling, the glass viscosity increases and the glass compacts as the amorphous molecular structure evolves towards the metastable equilibrium state of the supercooled liquid. The time required to achieve this state is a function of temperature history since the viscosity of the glass tends to inhibit "stabilization". At very high temperatures, "structural relaxation" occurs almost instantaneously, but as the temperature decreases and the viscosity increases, the stabilization time becomes longer. If cooling continues, at some point the viscosity becomes so great that the compaction cannot keep pace with the rate of cooling.

DISCLAIMER

This marks the upper limit of what is commonly called the glass transition region. Since this process is thermal history dependent, glasses cooled at slower rates will exhibit glass transition at lower temperatures than glasses cooled at higher rates (i.e., the glass structure is effectively given more time to relax). As the glass continues to be cooled, the viscosity ultimately becomes so high that the molecular structure is for all reasonable time scales "frozen". This marks the lower bound of the glass transition zone.

The fact that glasses are viscoelastic materials means that they assume characteristics of both elastic solids and viscous liquids depending upon the temperature and time frame of reference. During steady state glass processing at temperatures well above the glass transition temperature, Tg, the response is that of a viscous liquid with a temperature-dependent viscosity. In this regime, nonlinearities may be found under conditions of high confining pressure or high shear rates (e.g., shear thinning) [2,3]. At the lower temperature extreme, when glass is cooled well below the glass transition temperature, the material behaves as a brittle elastic solid exhibiting no observable time dependence. However, within the temperature domain broadly encompassing the glass transition zone, viscoelasticity becomes apparent.

VISCOELASTIC MODEL OF GLASS

When glasses are subjected to thermal cycles in the vicinity of the glass transition region, they undergo two types of relaxation. The most obvious is stress relaxation due to the flow-like character of the viscous liquid. However, there is a second equally important phenomenon, volume relaxation, which is driven by the change in structure of the glass (i.e., structural relaxation). The volume relaxation is thermal-history dependent and is the underlying cause for stresses generated when glasses are not heated or cooled uniformly. Under these conditions, the effective thermal expansion coefficient varies from point to point throughout the material. Because glass has such a low fracture toughness, it is the maximum tensile stresses that determine the durability of a glass part. Hence, to obtain accurate stress analyses when glasses are processed in a nonuniform, transient thermal environment (e.g., annealing, tempering, forming, etc.), viscoelastic models of glass with structural relaxation are needed. Traditional elastic, elastoplastic, and viscoplastic models do not incorporate these relaxation mechanisms. Moreover, this also emphasizes the importance of being able to predict accurate thermal histories in a manufacturing analysis. The thermal and mechanical history can have a profound influence on the ultimate shape and stress state of the material.

A linear viscoelastic treatment of thermorheologically simple materials under nonhomogeneous temperature fields that result from the solution of the usual heat conduction equation in the absence of thermodynamic coupling was presented by Moreland and Lee [4]. They found that it was possible to define a "pseudo" or "reduced" time scale, that in general is a function of both real time and space variables, whereby the constitutive equation, be it a differential form or integral equation, was the same as that at constant temperature in terms of real time. The three dimensional integral constitutive equations, written in indicial notation, defining the stress at a material point in a thermorheologically simple material undergoing small deformations and assumed to be free of stress and strain at time zero are

$$s_{ij}(t) = 2\int_0^t G[\xi(t)-\xi(\tau)]\frac{de_{ij}}{d\tau}d\tau \qquad (1)$$

$$\sigma_{kk}(t) = 3\int_0^t K[\xi(t)-\xi(\tau)]\frac{d}{d\tau}\{\varepsilon_{kk}-\Theta\}d\tau \qquad (2)$$

In these equations, s_{ij} is the deviatoric stress, σ_{kk} is the trace of the Cauchy stress tensor, e_{ij} is the deviatoric strain tensor, Θ is the volumetric thermal strain, K is the bulk stress relaxation modulus, G is the shear relaxation modulus, t is time, and ξ is the reduced time variable. Narayanaswamy [5] extended the framework of thermoviscoelasticity to depict the added volume relaxation in inorganic glasses by including fictive temperature, T_f , as an internal state variable and by using a new structural relaxation function, M(t). Through the dependence of the shift factor, Φ, on the fictive temperature in the definition of the reduced time variable, the structure of the glass is able to modulate the rates of stress relaxation:

$$\xi(t) = \int_0^t \Phi[T(s), T_f(s)]ds \qquad (3)$$

$$ln\,\Phi[T(t), T_f(t)] = \frac{xH}{R}\left\{\frac{1}{T_r}-\frac{1}{T(t)}\right\} + \frac{(1-x)H}{R}\left\{\frac{1}{T_r}-\frac{1}{T_f(t)}\right\} \qquad (4)$$

In this equation, H is the activation energy, R is the ideal gas constant, T_r is the reference temperature, T is the absolute temperature, and x is a dimensionless constant (between 0 and 1) which divides the total activation energy into glassy and liquidy parts. The fictive temperature changes are also used to compute the volumetric thermal strain history:

$$\Theta[T(t), T_f(t)] = 3\int_{T(0)}^{T_f(t)} \alpha_l(T')dT' + 3\int_{T_f(t)}^{T(t)} \alpha_g(T')dT' \qquad (5)$$

where α_l and α_g are the liquid and glassy linear expansion coefficients, respectively. The fictive temperature is defined through its own constitutive equation using a structural expansion coefficient, α_s :

$$\int_{T_f(t)}^{T(t)} \alpha_s(T')dT' = \int_0^t \alpha_s M[\xi(t)-\xi(\tau)]\frac{dT}{d\tau}d\tau \quad (6)$$

$$\alpha_s = \alpha_l - \alpha_g \quad (7)$$

It is worth noting that Equation (6) is intrinsically nonlinear since the reduced time variable itself is a function of fictive temperature. Numerical schemes for accurately approximating the preceding constitutive equations have been documented [6-9]. For the purpose of numerical integration, the relaxation functions K(t), G(t), and M(t) are typically written as a Prony series (i.e., an exponential series expansion).

THERMAL/STRUCTURAL MODELING

Thermal analyses are critically important for defining the temporal temperature distribution of glass during complex manufacturing processes. Heat transfer mechanisms and boundary conditions in a numerical model must accurately reflect processing and manufacturing conditions to provide the structural analyses with realistic material histories from which to compute viscoelastic deformations and stresses. The requisite coupling of the thermal/structural analyses varies depending on the needs dictated by the individual problem. In problems where the glass geometry is not changing significantly (i.e., there is no flow and no contact surfaces are added, removed, or changed) the thermal and structural analyses can be executed independently with separate computer codes. Since transient finite element analyses are performed by marching solutions forward in time, the preferred time stepping for the thermal analyses is not necessarily the same as that desired for the structural computations. Separating the two analyses permits optimal time stepping for each application. The structural analyses are then performed by reading the time planes of temperatures obtained from the thermal code and interpolating as need be to define intermediate results consistent with the times needed for the structural time-stepping. In situations where a single compatible mesh cannot be identified for both the thermal and structural analyses, it also is necessary to perform a spatial interpolation of temperatures from one mesh to another. If the geometry changes significantly during the course of the manufacturing process, then the thermal and structural analyses must be tightly coupled.

EXAMPLES OF LASER SEALING APPLICATIONS

There are situations where it is advantageous to be able to heat a glass preferentially either to reduce production costs or to protect delicate components from excessive heating during sealing. In this capacity, lasers can be quite effective. Two such applications have recently arisen at Sandia National Laboratories, one of which has been modeled and will be discussed in detail in the next section.

The first example involved a high-power, fiber-optic connector being designed as part of an optical firing system. In this design, glass was used to seal an optical fiber to an alumina ferrule. The seal was made by locally heating the end of the alumina ferrule with a laser so as to melt a cylindrical glass preform that was slipped over the fiber and that spanned the radial gap between the fiber and ferrule. When melted, this glass preform made a hermetic seal.

The second application involved flat panel displays. Here, laser sealing was investigated to determine whether two glass substrates could be sealed directly together by preferentially heating adjacent edges. This autogenous seal was posed in contrast to the use of an oven sealing process where a low temperature, glass frit was used to make the hermetic seal between substrates. In the course of this research project, thermal/structural analyses were performed to estimate the magnitude of the thermal stresses during a laser sealing operation.

MODELING LASER SEAL IN GLASS SUBSTRATES

A graphic defining the proposed laser sealing problem is shown in Figure 1. Two soda-lime glass substrates are

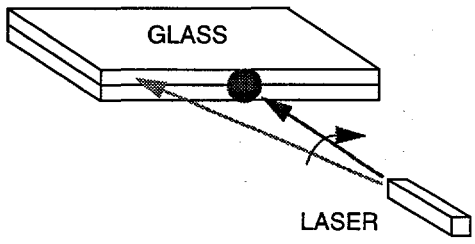

Figure 1. Schematic of Laser Sealing Operation

stacked on top of each other and a CO2 laser is focussed on the interface between the substrates. The laser spot starts at one corner and slowly travels along the length of the side. For testing purposes, relatively small substrates (1" square and 3/32" thick) were selected. The laser power was 10 watts, and 45 seconds was required to seal one edge of the panel.

For analysis purposes, a symmetry condition was invoked on the interface between substrates, and only the top substrate was modeled. Furthermore, it was assumed that any glass flow along the interface was negligible, and the analyses were performed as a one-way coupled problem. First, the thermal analysis was performed using a three-dimensional thermal finite element code, COYOTE II [10], and then the temperature results were passed to a three-dimensional structural finite element code, JAC3D [11], where the viscoelastic stresses and deformations were computed. A common mesh consisting of 5400 elements and 6930 nodes was used for both the thermal and structural analyses. The viscoelastic properties for the soda-lime glass were collected from the open literature [9,12].

The laser energy imparted to the glass substrates was modeled as a volumetric source. The heat source from the traveling laser was simulated by applying trapezoidal-shaped pulses along the sealing path. This approach discretely models a continuous moving laser by sequentially activating a string of pulses spread across segments of finite elements spanning the length of an edge. As each segment pulse turns on and off, there is the effect of a moving heat source. The

ramp time and duration of each pulse is determined based on the travel speed of the laser. The magnitude of the pulses is based on the spot size, energy transfer efficiency, and operating power of the laser. Figure 2 shows schematically the volumetric heat pulse approach used for the thermal analysis. Note that the pulses overlap at the midpoint of the ramps. This provides continuity in the rate at which energy is provided to the material, closely representing the actual sealing process. The total ramp time (both up and down) is 20% of each pulse cycle. The remaining 80% defines the duration of time that the pulse is at full power over each segment of pulse elements. This scheme results in the proper amount of energy (Joules) being deposited in each segment.

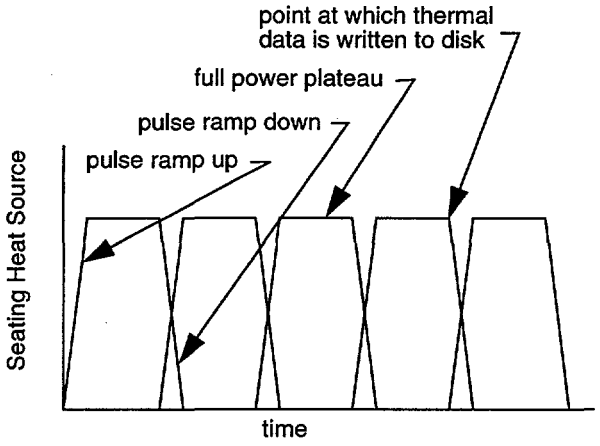

Figure 2. Energy Pulses to Simulate Moving Laser

The boundary conditions for the thermal analysis included natural convection and radiation to the surroundings/furnace. Simple convection correlations for flat plates [13] and gray body radiation relations [14] were used to estimate the boundary effects. Since a one-way coupling scheme was used between the thermal and structural analyses, the temporal and spatial temperature data were written at discrete times during the analysis. The frequency of temperature output was once per pulse, at the start of the ramp down (see Figure 2), and then at a reduced frequency during the subsequent cool-down period.

In the first set of analyses, the glass plates were assumed to be laser sealed in a laboratory, room temperature (20°C) environment. The laser produced maximum edge temperatures in the range 700-800°C. As expected, this produced severe thermal gradients along the edge of the substrates. Contour plots of the temperatures and maximum principal stresses computed after 40 seconds of laser sealing are provided in Figure 3. Several important observations can be made. The location of the maximum temperature corresponds to the position of the laser spot. In this general locale, the temperature gradients are the highest. Because glass has such a low fracture toughness, it is the magnitude of the maximum principal stress that relates most closely to brittle fracture. As seen in the stress plot from Figure 3, the maximum tensile stress is over 13000 psi (94 MPa). This value is well in excess of what would normally be expected to produce cracks in the glass. Moreover, the maximum stress is located well behind the location of the laser spot in a region that has cooled substantially. This is to be expected since the glass nearest the laser spot is hottest, being well above the glass transition temperature. Here, stresses can readily relax as the glass viscosity is low enough for some viscous dissipation. Note also the appearance of a slight halo of stress surrounding the location of the laser spot where the material is cool enough for the thermal gradients to generate some significant stresses. When experiments were conducted by attempting to seal the glass substrates in a room temperature environment, the glass cracked badly along the edges of the panel as soon as the glass started to cool.

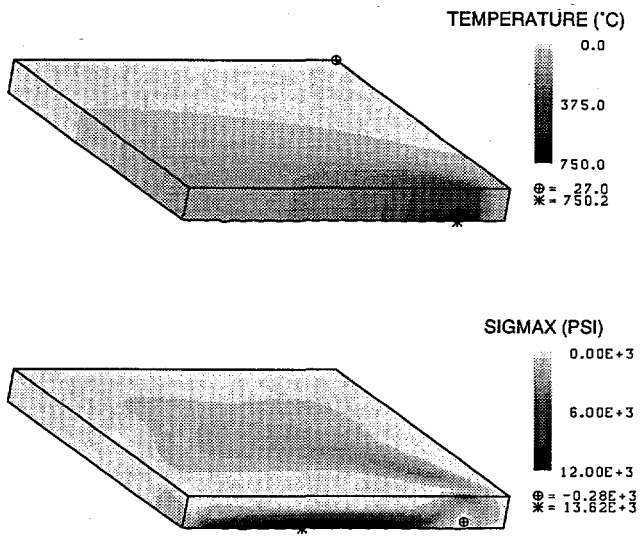

Figure 3. Contour Plots of Temperatures and Maximum Principal Stresses Computed 40 Seconds into the Room Temperature Laser Sealing Operation

Since both the coupled finite element analyses and experiments detected problems when attempting to produce a laser seal with glass substrates initially at room temperature, a second processing scheme was considered. This scheme was intended to determine whether the thermal stresses generated during rapid localized heating and cooling below Tg could be substantially reduced by imposing a lower bound on the temperature. The coupled thermal/structural model assumed that the sealing operation was performed in an oven environment at an elevated ambient temperature where the substrates had been uniformly heated to 450°C prior to sealing. In principle, after the laser sealing operation is completed, the furnace then can be cooled slowly to anneal the substrates further. The corresponding temperature and maximum principal stress predictions are plotted in Figure 4. Once again, results were taken 40 seconds into the sealing operation. Noticeably different between the two analyses is the magnitude of the maximum temperature. Although the energy input is identical for both cases, the difference in ambient temperature is sufficiently high to account for the 250°C increase in maximum temperatures apparent in

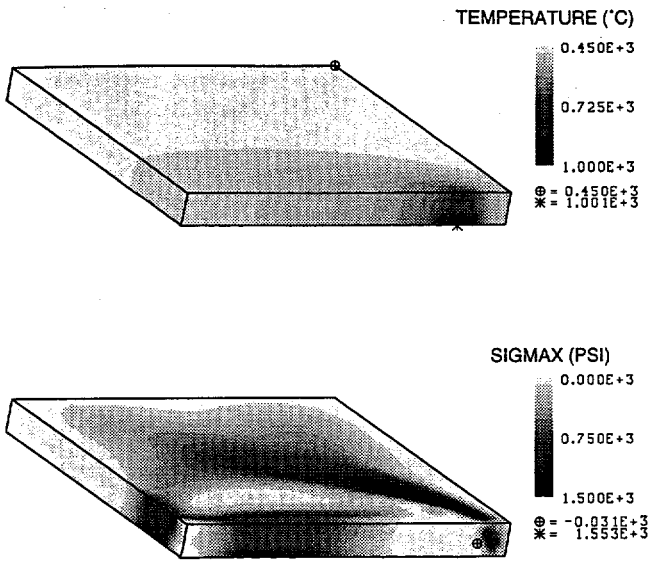

Figure 4. Contour Plots of Temperatures and Maximum Principal Stresses Computed 40 Seconds into the Laser Sealing Operation at a Bias Temperature of 450 °C

Figure 4. However, the more interesting changes occurred in the stress state where the maximum tensile stress decreased by about a factor of eight. Soda-lime glasses have an annealing point in the vicinity of 540°C and undergo volume relaxation (i.e., structural relaxation) at temperatures down to 300-350°C. When sealing at a bias temperature of 450°C, the entire plate is viscoelastic and susceptible to variable volumetric relaxation induced by the thermal history. This is in marked contrast with the room temperature sealing problem where most of the substrate remains elastic. A second major difference arises from the fact that when the laser sealing is conducted in the 450°C oven environment, most of the severe thermal gradients are incurred in a temperature regime near or above the glass transition temperature where stresses can freely relax. This accounts for the lower stresses in Figure 4. In fact, higher stresses (1940 psi or 13.4 MPa) were generated 45 seconds after the laser was turned off as the substrates cooled below Tg. The magnitude of these stresses is still substantially lower than those generated by the room temperature sealing process. During the room temperature sealing, the temperatures are generally lower in magnitude (i.e., closer to Tg and below), and the thermal gradients are more severe, not being limited to the bound set by the higher ambient temperature. This tends to generate higher (elastic) stresses which do not relax. When experiments were conducted by sealing the glass substrates in a 450°C ambient environment, they remained crack-free.

CONCLUSIONS

Glass processing analyses can be performed with a suitable combination of fluid/thermal/structural modeling tools. In situations where flow can be neglected, a simple one-way code coupling between thermal/structural finite element codes can be used to evaluate processing parameters based on the thermoviscoelastic behavior of glass. For the application presented where a laser was used to make an autogenous seal between two glass substrates, the importance of ambient temperature conditions was demonstrated. When sealing at 450°C as opposed to room temperature, the tensile stresses are lowered because most of the severe thermal gradients are attained while the glass is at temperatures above Tg. Moreover, the magnitude of the thermal gradients that are below Tg are reduced by the higher ambient temperature limit.

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