THERMAL STRESSES AND RELATED FAILURE MECHANISMS: BRIDGE-WIRE INITIATORS

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17. Abstract

Cracks of the cylindrical glass-to-metal seals (GTMS) of pyrotechnic bridge-wire initiators could present a path for moist gases to diffuse into the critical interior region of the initiator, potentially leading to wire degradation, delayed ignition, or a no-fire condition. The goal of this research is to determine if welding the initiator output can onto the initiator header assembly could produce thermal stresses in the glass sufficient to cause cracking of the GTMS. A finite element analysis (FEA) solution is used to model the transient heat transfer and temperature distribution in the initiator assembly during the welding process. The thermal stresses are calculated using a mechanical analysis once the temperature distribution is determined. Compressive stresses induced by pressing the header assembly into the output can are also investigated using a closed-form solution. While predicted thermal stresses are shown to exceed the range of glass strengths reported in the literature, superposition of the compressive stresses due to the press-fit and the residual stresses due to the thermal stresses produced during welding are shown to be on the same order as the reported glass strengths. It is shown that when initiators are overheated during welding, failure of a portion of the pin-glass interface may occur.

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INTRODUCTION

Airbags were responsible for saving nearly 17,000 lives between 1975 and 2004 [1]. Currently about 150 million vehicles in the United States are equipped with airbags, and are expected to function properly during a long vehicle life span. The pyrotechnic initiator within the airbag is responsible for deploying the airbag in crash situations. In this particular application, it is of critical importance that they perform reliably without failure or diminished performance for the intended service life of the vehicle, usually 15 years [2]. Due to the susceptibility of critical internal components to corrosion induced by moisture or other contaminants, bridge-wire initiators are intended to be hermetic and impervious to the surrounding environment.

The integrity of the bridge-wire and its surrounding pyrotechnic charge are critical when considering the hermetic behavior of initiators. Moisture in the bridge-wire region may lead to corrosion and degradation of the bridge-wire [3-5] and may also result in degradation of certain pyrotechnic materials. In addition, it is possible that decomposition of some pyrotechnic materials in the presence of moisture may exacerbate corrosion of the bridge-wire [6]. Moisture may be inherent in the material constituents of the device, it may be a product of decomposition of certain pyrotechnic materials, or it may be introduced through an external leak [7]. When considering the possibility of leaks, of particular concern is the integrity of glass-to-metal seals which are a common design attribute of bridge-wire initiators. Studies have shown that these seals may be found to contain cracks or other flaws [8,9], as can be seen in Figure 1.
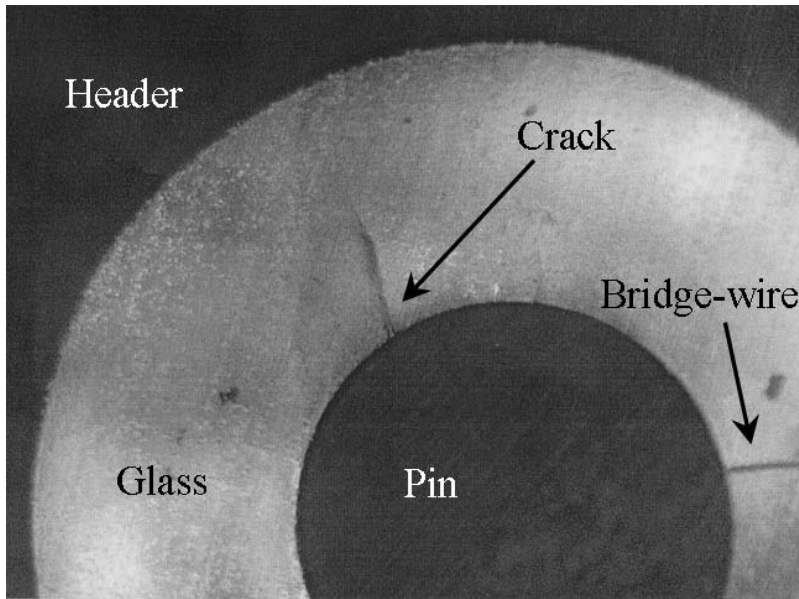
Figure 1 - Crack in initiator glass-to-metal seal

To better understand some of the technical issues surrounding the importance of the glass-to-metal seal in bridge-wire initiators, it is informative to review common design characteristics and certain assembly details of these devices. The basic components of a bridge-wire initiator, illustrated in Figure 2, include: a pyrotechnic output can, a bridge-wire heating element, a glass-to-metal seal (GTMS) to isolate the electrical pin, a metal header, and a synthetic over-molding. There is generally at least one electrode (pin) passing through the header. This electrode is insulated from the metal base by the glass. A fine bridge-wire, typically about 20 μm in diameter is resistance welded to the interior edge of the pin, with the opposite end of the bridge-wire welded to the header. Given the application of an appropriate electrical signal, the bridge-wire is rapidly heated, resulting in ignition of the pyrotechnic charge. Since certain features, such as the shape of the electrical pins, the geometry of internal glass-to-metal seals, and the design of the header assembly may differ between different manufacturers, the initiator shown is intended to be representative of those commonly used in the automotive industry. More design details concerning initiators for both automotive and aerospace applications can be found elsewhere [10].
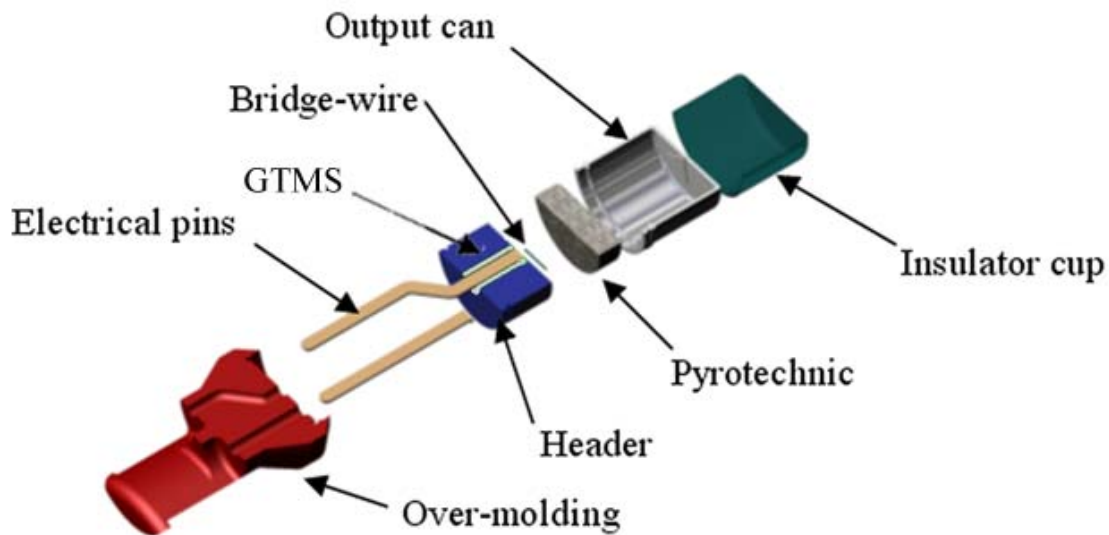
Figure 2 - Basic elements of a bridge-wire initiator.

During assembly, the header is pressed into the output can and the entire assembly is held in this position while the two sub-assemblies are sealed together, usually by welding. At this point, the initiator is considered sealed and is subjected to a leak test to verify hermetic integrity, and a properly executed leak detection methodology may reveal a damaged GTMS that may otherwise allow moist gases from the surrounding environment to traverse along the surface of an electrical pin and penetrate into the bridge-wire region. It is also conceivable that cracks, fissures, or other flaws may extend through the GTMS, also permitting gases to diffuse into the bridge-wire region. The purpose of this paper is to focus on the GTMS with respect to the stresses resulting from thermal changes during the manufacturing process. Thermal stresses that may be caused by welding the output can onto the header were not considered in this research; rather, the intent was to use basic mechanics to explore the possibility of thermal stresses great enough to cause cracks during GTMS manufacture.

The principal problems of GTMS have long been known. Hull and Burger (1934) [11] outline two requirements for an effective GTMS:

"(1) The glass must 'wet' the metal.

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(2) The stresses resulting from thermal expansion and contraction must not exceed the tensile strength of the glass."

They compared calculated and experimental stresses for an external seal (internal wire, external glass) loaded by weights and show reasonable agreement between the two.

Borom and Giddings [12] consider a seal similar to Figure 1, but of smaller dimensions than examined in this work and examine the effects of expansion characteristics of component materials. Their main assertion is that matching expansion characteristics between pin and glass serves to improve resistance to fracture.

Kokini [13] uses finite elements to determine non-dimensional stresses in GTMS during large temperature excursions. He conducts thermal shock tests to establish the strength of sample seals

Lee, Chen, and Hung [14] use the Laplace transform and finite difference methods to determine the transient response of one-dimensional axisymmetric quasi-static coupled thermoelastic problems. Similarly, Jane and Lee [15] use finite difference and Laplace transform methods to describe the thermoelasticty of concentric finite-length cylinders. Their two-dimensional axisymmetric analysis describes the condition where there is a prescribed surface temperature and no surface tractions.

METHODS

Initiator Description

There are no standard physical geometries of header assemblies. The geometry shown in Figure 3 is representative of the physical geometries common in the industry and available in sufficient quantities for testing. The three components of the initiator analyzed in this research were the pin, made of alloy 52, a 50.5% Ni-Fe alloy; the glass, made of 8061 glass; and the header, made of 304L stainless steel. The material properties of the components of the initiator are shown in Table 1. This initiator geometry was selected due to its simplicity of design, as the three elements are concentric, and its availability in quantities sufficient for testing.

Because actual manufacturing methods of initiators are considered proprietary, two processes were chosen to model possible methods of manufacturing the initiators. In the first method, the

pin, preformed glass, and header are assembled at room temperature, placed in a furnace, heated above the glass transition point of the glass and cooled to room temperature. The second method heated the glass above its glass transition point and then poured the molten glass into an assembly that held the pin and header. Though these two methods are not inclusive of all manufacturing methods, they are representative and will provide insights into reducing the possibility of failure.
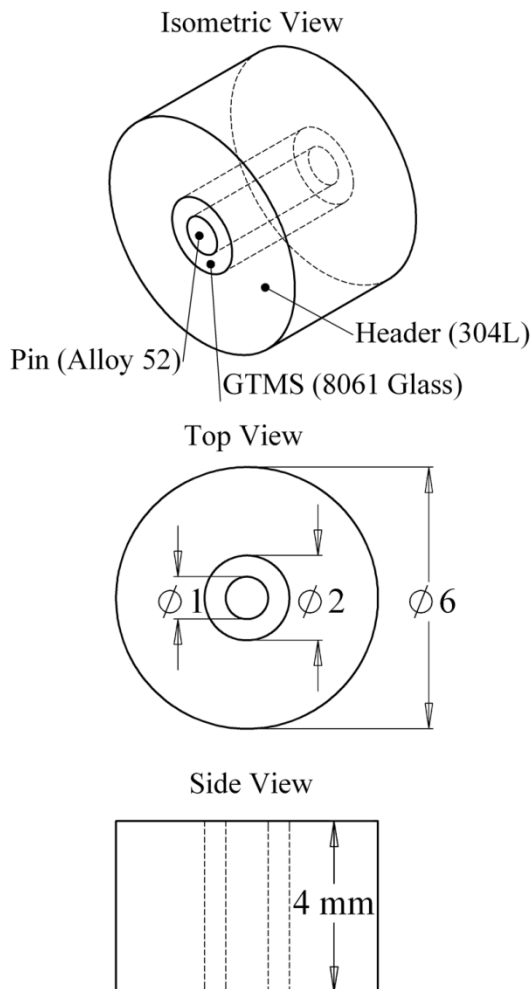
Isometric View

Header (304L)

Pin (Alloy 52)

GTMS (8061 Glass)

Top View

$\phi 1$ $\phi 2$ $\phi 6$

Side View

4 mm

Figure 3 - Idealized header/electrode/GTMS assembly.

Table 1 - Material Properties of Initiator Components

Material Property	Alloy 52 [16]	8061 Glass [17]	304L Stainless Steel [18]
E, GPa	165.5	70	196.5
ν	.29	.22	.29
α, μm/m/K	10	9.3	18
ρ, kg/m^3	8304	2600	8000
k, W/m/K	14	1	18
c_p, J/kg/K	502	737	500

Closed Form Solution

A closed form solution (CFS) was used to determine the basic magnitudes of stress that an initiator is subjected to during the manufacturing process. The closed form solution was based on the information presented in [19] and [20]. A two-dimensional solution was used, and involved the following fundamental assumptions:

- Stresses were located in the center of the initiator.

- Plane stress conditions existed.

- The materials were elastic, isotropic, and homogeneous and had temperature-independent material properties.

- Perfect adhesion was present at both the bond between the pin and glass and the bond between the glass and header.

- There was no interphase region at either interface.

- Any interaction effects among the parameters are negligible and can be ignored (i.e. changing one of the parameters does not change the magnitude of the others).

The closed form solution was used to calculate the changes in dimensions of the components of the initiator due to the temperature change, using Eq. (1). The interfacial pressures were then calculated using Eq. (2). Eq. (3) was used to ensure that the surfaces of the cylinders remained in

contact throughout the manufacturing process. The magnitudes of the radial and tangential stresses throughout the initiator were determined with Eq. (4) and Eq. (5), respectively.

$$\delta_t(r) = \alpha r(\Delta T) \tag{1}$$

$$\delta_p(r) = \frac{r}{E(b^2 - a^2)}\left[(1-v)(p_1 a^2 - p_2 b^2) + \frac{(1+v)a^2 b^2}{r^2}(p_1 - p_2)\right] \tag{2}$$

$$r_{1\_o} + \delta_{1\_t} + \delta_{1\_p} = r_{2\_i} + \delta_{2\_t} + \delta_{2\_p} \tag{3}$$

$$\sigma_r(r) = \frac{p_1 a^2 - p_2 b^2 - \dfrac{a^2 b^2(p_2 - p_1)}{r^2}}{b^2 - a^2} \tag{4}$$

$$\sigma_t(r) = \frac{p_1 a^2 - p_2 b^2 + \dfrac{a^2 b^2(p_2 - p_1)}{r^2}}{b^2 - a^2} \tag{5}$$

The closed form solution was first used for a parametric study to determine the effects of changing the initiator component dimensions (b of the pin, glass, and header), the elastic moduli (E of the pin, glass, and header), and the material coefficients of thermal expansion (α of the pin, glass, and header) [21]. Nine cases were analyzed, while for each case one of the nine aforementioned values was varied. While one value was varied, the remaining eight were maintained at values representative of real materials used in initiators. The ranges for the variables can be seen in Table 2. These ranges were not intended to represent actual initiator materials, but were chosen to encompass all possible and reasonable materials. The decision was made to ignore any interaction of properties for several reasons. Most importantly, the effect that changing one property has on the others was unknown. The intent of the work was to clearly show how varying the parameters changed the stresses, not to predict failure of different types of initiators. In addition, investigating interaction effects, such as how changing coefficient of thermal expansion affects the elastic modulus, was beyond the scope of the work and would require more resources than were available.

In each of the nine cases, only the minimum and maximum stresses within each component of the airbag initiator were calculated. These values coincided with the extreme radii of each component (pin, glass, header). The quantity of different stress values under consideration was

also reduced by the mechanics of materials equations: at a boundary, the radial stress must equal the pressure at that location, and when the inner radius of a cylinder equals zero, the radial and tangential stresses throughout that component are equal. These simplifications left six different critical stress values to consider, their locations identified in Figure 4. They are:

- the radial stress in the glass at the glass-header (GH) interface, that was equal to the radial stress in the header at the glass-header interface,
- the radial stress in the glass at the pin-glass (PG) interface, that was also equal to both the radial and tangential stresses throughout the pin,
- the tangential stress in the glass at the PG interface,
- the tangential stress in the glass at the GH interface,
- the tangential stress in the header at the GH interface, and
- the tangential stress in the header at the outer surface of the initiator.

Table 2 - Range of varying variables for parametric studies

Case	Varying Variable	Range
1	α of Pin	5-15 [μm/m/K]
2	α of Glass	4.65-14 [μm/m/K]
3	α of Header	9-27 [μm/m/K]
4	E of Pin	82.8-248 [GPa]
5	E of Glass	35-105 [GPa]
6	E of Header	98.3-295 [GPa]
7	b of Pin	0.05-0.95 [mm]
8	b of Glass	0.55-3.05 [mm]
9	b of Header	1.05-4.2 [mm]

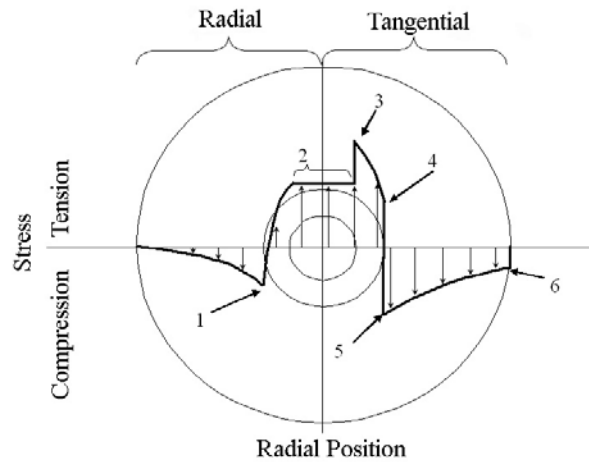## Critical Stress Locations

Figure 4- Stress profiles and critical stress locations considered during parametric study.

The closed form solution was also used to analyze two different scenarios of the airbag initiator undergoing uniform cooling. The first scenario was when all three components of the initiator were stress-free at a temperature of 467ºC, with the initiator then cooled to 20ºC. This scenario represented the airbag initiator being assembled in a furnace. The high temperature corresponds to the glass transition temperature of the glass. The second scenario was when the glass was stress-free at 467ºC, the pin and header were both stress-free at 20ºC, and the glass was cooled to 20ºC. This scenario represented molten glass being poured into the metal components at room temperature, and the whole assembly cooling to room temperature. This analysis assumed that initially the glass was stress-free at its glass transition temperature, 467ºC, and that it was cooled to room temperature, 20ºC, the temperature where the header and pin were stress-free. For mathematical analysis, the change in temperature of the header and pin was 0ºC and the change in temperature of the glass was -447ºC.

The closed form solution resulted in high stresses in the GTMS for the case of pouring molten glass; these results will be presented in the Results section. Since many assumptions were made for the closed form solution, a more robust approach was needed that would account for the effects of transient cooling and the three-dimensional geometry of an initiator. This was done with finite element analysis (FEA), as presented below.

Finite Element Analysis

The assumptions of the closed form analysis neglected the possibility of uneven cooling of the airbag initiator. The closed form analysis also neglected possible three-dimensional effects, such as stresses induced by a mismatch of thermal deformation on the ends of the initiator at the interfaces between metal and glass. A FEA was chosen to further analyze the airbag initiator in order to account for three-dimensional and transient heat transfer effects. These analyses were based on the same parameters as the finite element analyses that can be found in Refs. [21] and [22].

ALGOR-FEMPRO version 13.3 was used for the FEA. The mesh is shown in Figure 5. Material property values from Table 1 were input into ALGOR. Consistent with the closed form solution, two manufacturing processes were examined. For each manufacturing process, two types of models were used. The first model type used a combination of default nodal temperatures, specified for each material. In addition, the stress-free reference temperatures for the three different materials were input to the program in order to perform a linear stress analysis. The second model type established the stress-free reference temperatures and nodal temperatures in the same manner, but used transient heat transfer to determine the temperature distribution within the airbag initiator. The temperatures found with both types of models were then used to determine the state of stress within the airbag initiator as the temperatures changed with time.
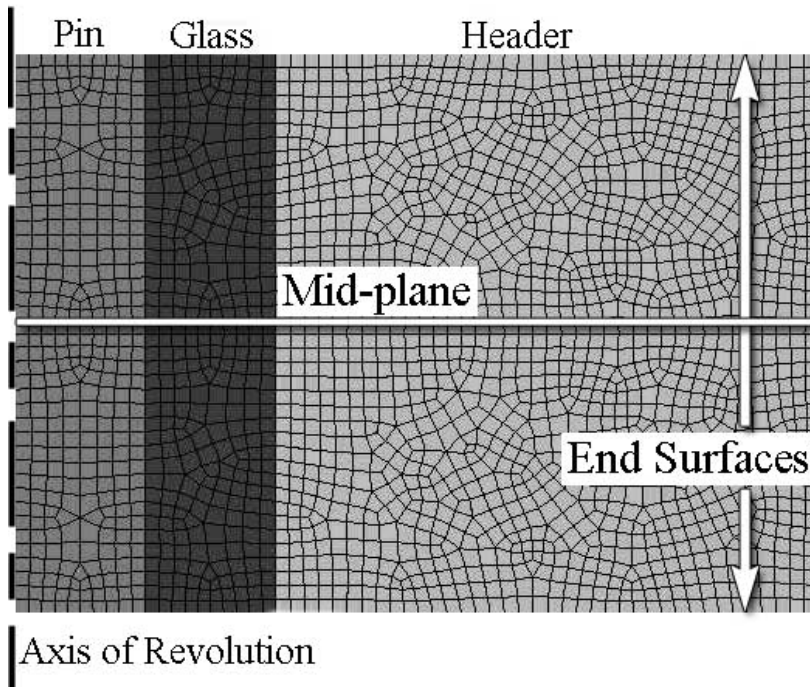
Figure 5 - Axisymmetric finite element mesh of the airbag initiator.

The first finite element model analyzed the initiator starting at a uniform high temperature and in a single step reaching room temperature and was called the Uniform Initial Temperature with Lumped Analysis (UITLA) Model. The stress-free reference temperature of the three components of the airbag initiator was defined at 467ºC. The default nodal temperatures for all nodes were set to 20ºC.

The second model, an analysis of cooling the initiator components from a single temperature, while including the effects of thermal gradients, was called the Uniform Initial Temperature with Gradients (UITG) Model. The initial and default temperatures were the same as in the UITLA model. A convection coefficient, h, of 100 W/m^2/K was applied to the external surfaces of the initiator to produce temperature values as a function of time. A transient heat transfer analysis was then performed. This was followed by a mechanical analysis to calculate stresses as a function of time. The UITLA and UITG models simulate the manufacturing process where the pin, preformed glass, and header are heated and uniformly cooled.

The manufacturing process of pouring molten glass into the initiator was analyzed with the Molten Glass with Lumped Analysis (MGLA) model and the Molten Glass with Gradients (MGG) model. The MGLA model used the simplification that the glass begins at the glass transition temperature (467ºC), the header and pin begin at room temperature (20ºC), and in a single step the entire initiator cooled to room temperature. The nodal and stress-free reference temperatures of the 8061 glass were set at 467ºC and the nodal and stress-free reference temperatures of both the alloy 52 pin and stainless steel header were set at 20ºC.

For the MGG model, an analysis similar to the MGLA, but including thermal gradients due to the pouring of molten glass into the initiator was performed. A convection coefficient, h, of 100 W/m^2/K, was applied to the external surfaces of the initiator and then a transient heat transfer analysis was performed where the entire assembly cooled to room temperature during a time period of 10 seconds. Finally, a mechanical analysis was used to calculate the stresses as a function of time.

RESULTS AND DISCUSSION

Closed Form Solutions

1. Parametric Study

The results of Case 1 (α_pin ranging from 5 to 15 μm/m/K) of the parametric study are presented in Figure 6. As the coefficient of thermal expansion of the pin increases, the tangential stress in the glass at the pin-glass interface becomes more compressive. The radial stress in the glass at the pin-glass interface becomes less compressive, but under this range of the coefficient of thermal expansion of the pin, the stress does not become tensile. Both the radial and tangential stresses in the glass at the glass-header interface are also compressive for this range of α. The results of the other 8 cases of the parametric study can be found in [21].
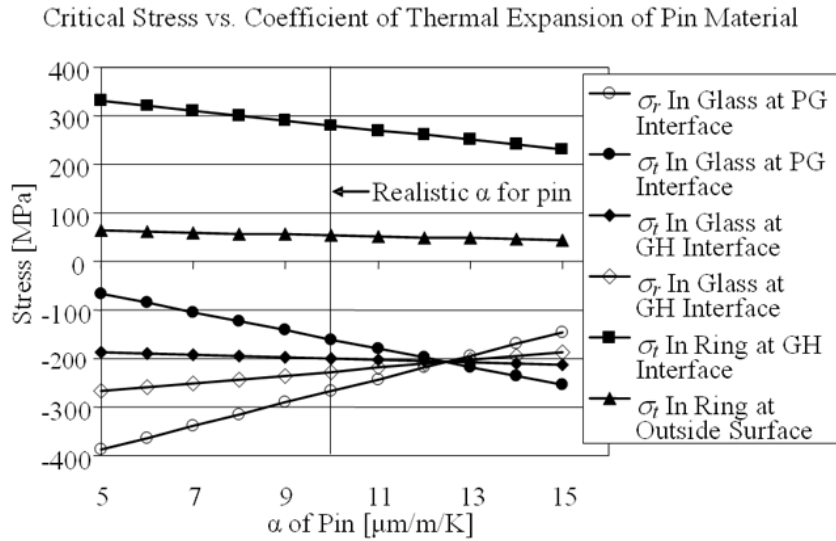
Figure 6 - Critical stresses from Case 1 of parametric study.

From the parametric study, the overall trends that increase the magnitude of compressive stresses in the glass can be identified. Ideally the initiator would be stress-free at room temperature, but if exact matching of coefficients of thermal expansion between the materials is not possible, it would be better to have a compressive stress within the glass than a tensile stress, since cracks are generally initiated when a tensile stress is present. Table 3 summarizes the trends in the parametric study that result in an increase of the compressive stress within the glass.

Table 3 - Summary of results of parametric study

Case	Trend
1	There exists a value of coefficient of thermal expansion of pin that results in all critical stresses in glass having equivalent magnitudes.
2	A decrease in coefficient of thermal expansion of glass results in larger compressive stresses in glass.
3	An increasing coefficient of thermal expansion of header results in larger compressive stresses in glass.
4	An increasing modulus of elasticity of pin results in larger compressive radial and smaller compressive tangential stresses in glass.
5	A higher modulus of elasticity of glass results in larger compressive stresses in glass.
6	A higher modulus of elasticity of header results in larger compressive stresses in glass.
7	A larger diameter of pin results in larger compressive stresses for three critical stresses in glass.
8	A smaller outer diameter of glass results in larger compressive stresses in glass.
9	A larger diameter of header results in larger compressive stresses in glass.

2. Closed Form Initiator Manufacturing Models

The results of the closed-form analysis of the uniform cooling of the airbag initiator are shown in Figure 7. It shows the radial and tangential stress profiles developed in the initiator as a function of radial position. The closed-form model shows that the entire component will be under radial compressive stress (left side of stress profile). The compression at the interfaces will help maintain a seal between the glass and the metal components in case there is not perfect adhesion. The entire GTMS is also under tangential compression. This will help to prevent radial cracking of the component. Since the glass is stronger in compression than in tension, the likelihood of failure due to uniform cooling of the entire initiator is low.
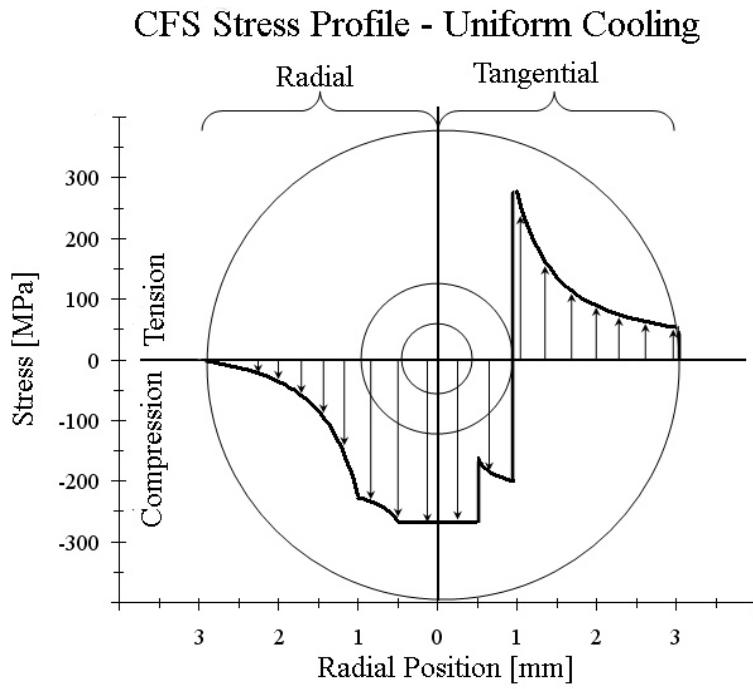
Figure 7 - Closed form solution tangential and radial stress vs. radial position for uniform temperature change from 467ºC to 20ºC.
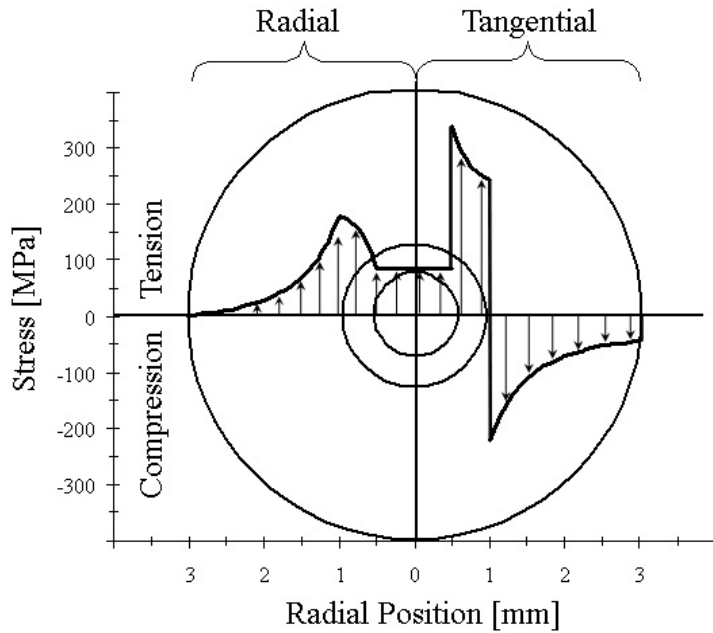
CFS Stress Profile - Pouring Molten Glass

Figure 8 - Closed form solution tangential and radial stress vs. radial position for pouring molten glass into initiator and cooling from 467ºC to 20ºC.

Figure 8 shows the results of the closed form analysis of pouring the molten glass into the space between the header and pin. This analysis shows that there are tensile stresses developed in the pin and glass. The entire initiator, with the exception of the outer surface, is under a radial tensile stress and could potentially cause separation of the glass from the metal at the interfaces. These tensile interfacial pressures (radial stresses) have resulted in a tangential tensile stress in the glass. The tangential stress at the inner surface of the glass is of greater magnitude than that of the outer surface due to the magnitudes of the interfacial pressures. The stress at the inner surface, 345 MPa, is 60% of the characteristic strength of the glass, 554 MPa [21].

The closed form analysis clearly shows the potential for tensile stresses in the glass to be developed. A FEA model was used to incorporate a two-dimensional geometry into, and further investigate this problem.

Finite Element Analysis

In the UITLA model, it was found that the entire pin and GTMS were under compression. The radial stress is essentially compressive throughout the entire initiator, as the maximum tensile stress is four orders of magnitude smaller than the maximum compressive stress. The tangential stress is compressive throughout the entire pin and glass, but has a maximum tensile stress of 447 MPa in the header along the entire glass-header interface, shown as location 1 in Figure 9. It should be noted that at the top and bottom end surfaces of the initiator, on the glass-header interface, locations 3 and 4 of Figure 9, the radial compressive stress is of a much higher magnitude than in the center of the initiator. This result is due to the convective cooling of the end surfaces of the initiator.
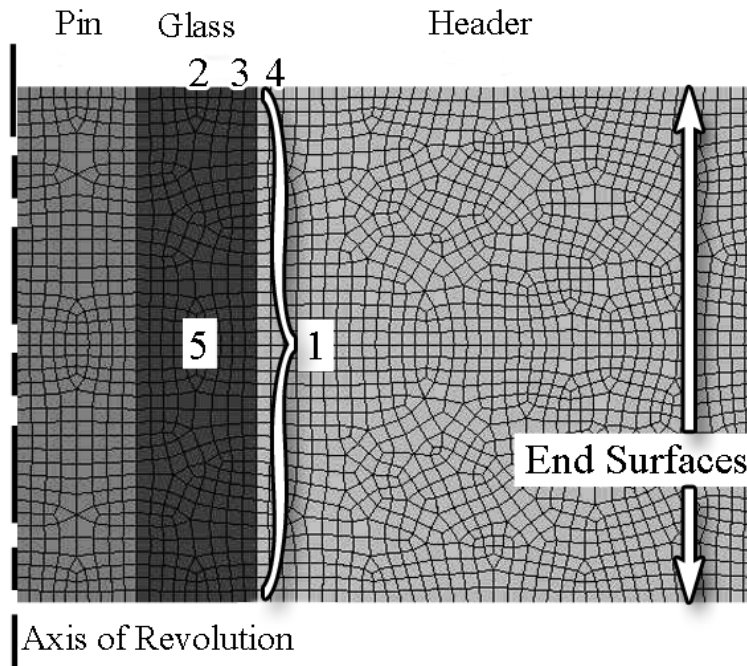

Figure 9 - Finite element analysis critical stress locations

Of the four models in this research, the UITLA model is most similar to, and agrees with, what was presented by Nattermann et al. [23], whose analysis included a pin that projected above and below the glass, and a header that projected below the glass. The profile of the radial stress contours and the magnitude of the radial stresses, in the area surrounding the upper glass-header interface agree between this work and the work of Nattermann et al. [23]. The stress profile from this FEA also shows agreement with the mechanics approach discussed earlier, as can be seen in

Figure 10. The tangential stresses shown in Figure 10, describing the FEA, were extracted from the horizontal mid-plane of the ALGOR model. The difference in the results for the FEA vs. CFS is due to the three-dimensional effects included in the FEA, as axial strains increase the stress in the radial and tangential directions proportionally to the axial strain. Since the header has a higher coefficient of thermal expansion than the pin, the glass-header interface is placed under more axial strain than the pin-glass interface. This results in more radial and tangential compressive stress near the glass-header interface than elsewhere.
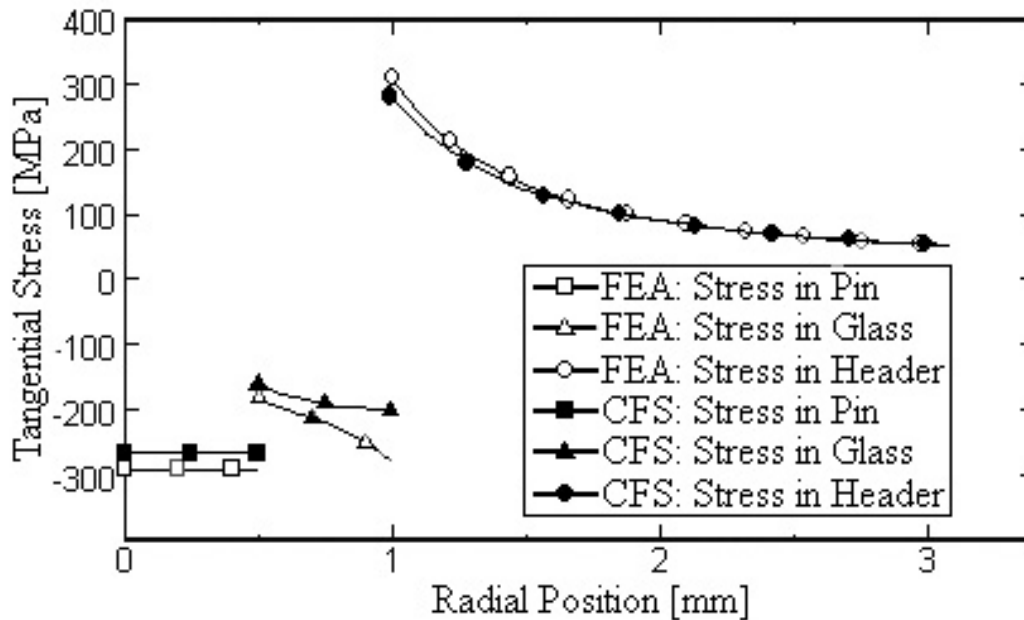

Figure 10 - Tangential stress vs. radial position for UITLA model and closed-form solution.

The UITG model found that radial and tangential tensile stresses occur in the glass. Again referring to Figure 9, the peak radial stress in the glass was 5.0 MPa, on the end surface at the interface of the glass and the pin, location 3. The peak tangential stress in the glass was 5.9 MPa, at the middle of the end surface of the glass, location 2. The stresses were greater at the end surfaces than at the mid-plane. It is important to note that the maximum tangential stress is greater than the maximum radial stress thus the likelihood of radial cracks, as shown previously in Figure 1, is greater.

From the MGLA model, the peak radial tensile stress in the glass was 280 MPa, on the end surface of the glass at the interface of the glass and header, location 2. The peak tangential tensile stress in the glass occurred at the same location, and had a magnitude of 420 MPa.

As expected, the MGG model predicted stresses equal to those in the MGLA model after cooling took place and equilibrium was reached. Peak stresses were seen 3.18 seconds into the 10 second analysis. At this time, the entire initiator was about 40°C. At the interface of the glass and header, locations 3 and 4, the radial stress had a peak of 310 MPa on the end surface. The maximum tangential stress occurred on the mid-plane, at the pin-glass interface, shown as location 5, and had a magnitude of 460 MPa. The maximum tangential stress on the end surface of the glass had a magnitude of 440 MPa and occurred at location 2. Table 4 summarizes the conditions when tensile stresses were predicted in the glass. The UITG model predicted tensile stresses, but they were insignificant when compared to those predicted by other models. Also note that the closed form solution for uniform heating, and the UITLA model, did not predict tensile stresses in the glass.

Table 4 -   Summary of Scenarios with Tensile Stresses in Glass

Model	Description of Manufacturing Scenario Modeled	Maximum Tensile σ_r [MPa]	Maximum Tensile σ_t [MPa]
CFS: Pouring Molten Glass into Initiator	Pouring molten glass then cooling	172	345
UITG	Heating pre-formed glass and initiator to uniform temperature then cooling	5	6
MGLA	Pouring molten glass then cooling	279	423
MGG	Pouring molten glass then cooling	315	456

CONCLUSIONS

This research predicts that radial cracks form in the initiator when molten glass is poured into the initiator or if the surface of the initiator is cooled more quickly than the center. If the coefficient of thermal expansion can be matched between the pin, glass, and header, the probability of failure of an initiator will be greatly reduced, as the likelihood of failure from non-uniform cooling is much less than that of failure due to pouring molten glass into the initiator. To reduce the probability of failure, a manufacturer should use processes that involve cooling the entire initiator from a given temperature in manufacture, and it should be cooled slowly to ensure that the temperature difference between the surface and interior is minimized. Using pre-formed glass components appears to be satisfactory. However, because tensile stresses can be caused by a number of factors, the exact manufacturing process needs to be carefully analyzed. It is imperative that molten glass not be poured into the rest of the initiator at room temperature, as the likelihood of failure of the initiator due to tensile stresses is high.

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