I-6 Stress in Glass-Indium-Glass Bi-Metallic Composite

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In electronic tube manufacturing industry, indium is used for cementing glass components to form vacuum-tight seals. To examine the effects of plasticity of indium on formation, distribution or release of stresses in seals, bi-metallic composites were formed from strips of various kinds of glasses by cementing with indium, and the stress was observed photoelastically.

The stress was nearly zero at the ends and reached maximum at the central parts of the composite. Stress in glass observed at room temperature was smaller than that calculated by assuming adhesion at the melting point of indium. During thermal cycle, the stress showed a hysteresis phenomenon distinctly.

The results were explained by putting several assumptions on the plastic behavior of indium and on the stress release in the composites by the flow of indium layer. It is concluded that the stress in the composite is mainly determined by yield strength of indium and dimensions or stiffness of glass components to be cemented.

1. Introduction

In the electronic tube manufacturing industry, indium is used for cementing glass components to form vacuum-tight seals. Owing to its low melting point (156°C), low yield strength and good wettability with glass, indium is capable of cementing together glasses with different thermal expansion coefficients or forming seals at relatively low temperatures. Vidicon with a photoconducting film on its face glass is an example. The effects of plasticity of indium on stresses in glass-indium-glass seals were examined experimentally.

2. Experimental Methods

Glass strips of $3\times10\times50$ mm in size were cemented by indium to form bi-metallic composites. The glasses used were fused silica, Kovar sealing and commercial plate glasses. The expansion coefficient of these glasses at room temperature was 7, 50 and 80×10^{-7}/°C respectively. The stress or photoelastic retardation in the composites was measured with a Babinet compensator (Fig. 1). For measurements at high temperatures, the composites were heated or cooled slowly in an electric furnace.

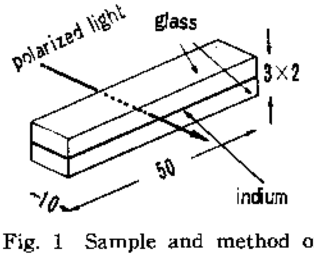

Fig. 1 Sample and method of photoelastic observation.

3. Experimental Results

3.1 *Stress distribution in a composite*

The edge of a fused silica-plate glass composite was inserted between crossed Nicols (Fig. 2). The distribution of dark and bright parts was hardly changed with the rotation of the composite, and in particular, when the composite was parallel to the direction of vibration of polarized light, the field of view was almost dark. Accordingly, the principal stesses seemed to be parallel or perpendicular to the cemented surfaces.

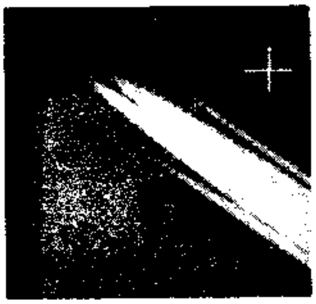

Fig. 2 Photoelastic field of view of a composite at an end of a composite between crossed Nicols. Cross shows direction of vibration of polarizer and analyzer.

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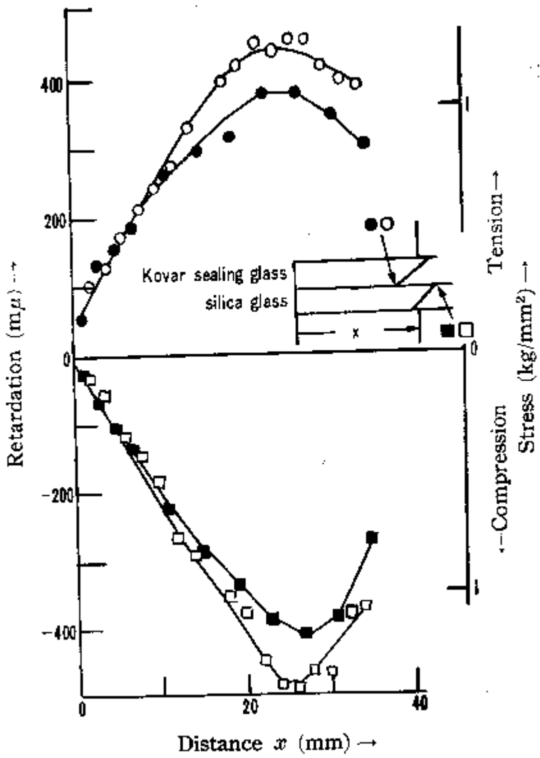

Fig. 3 Stress distribution in a composite. Filled signs: cooled in air. Open signs: cooled slowly in an electric furnace after cementing.

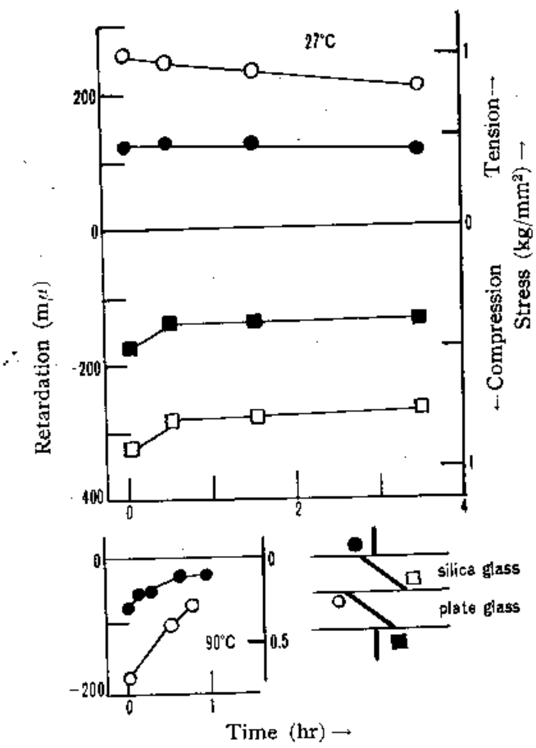

Fig. 4 Change of stress during soaking at various constant temperatures.

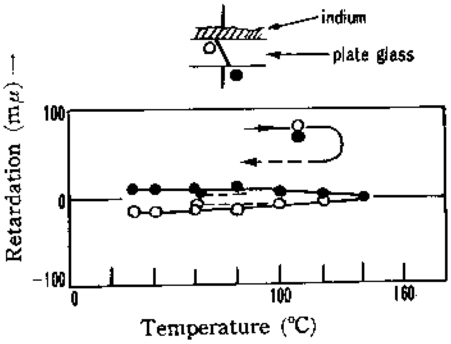

Fig. 5 Change of stress with temperature in a glass strip carrying a layer of indium.

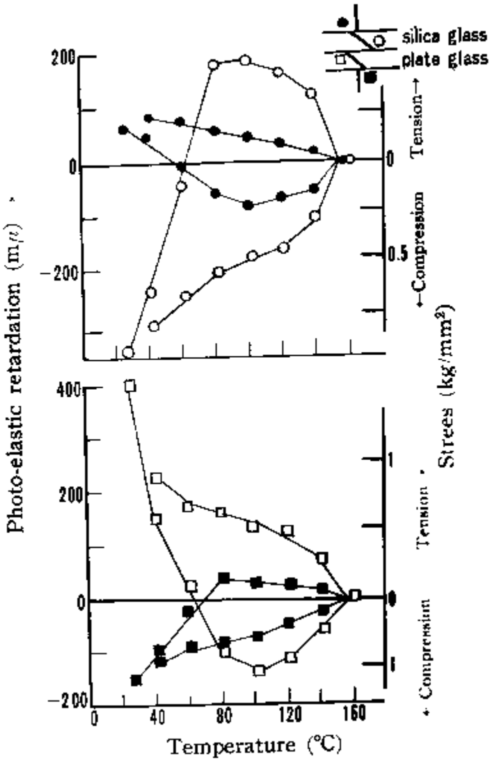

Fig. 6 Change of stress in a composite with temperature (at the central part).

The absolute values of stresses were, however, not uniform. The stresses were nearly zero at the end and became maximum at the central part (Fig. 3). The effect of cooling rate on stress distribution was not so distinguished.

3.2 *Stress relaxation at various constant temperatures*

A fused silica-plate glass composite was held at 27° and 90°C respectively. At 90°C its stress relaxed distinctly (Fig. 4).

3.3 *Stress caused by the sticking of indium*

A layer of indium about 0.5 mm thick was

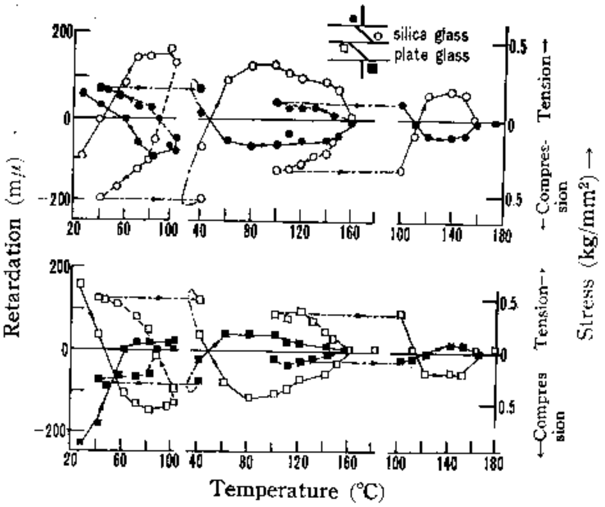

Fig. 7 Change of stress in a composite with temperature (at the part somewhat near the end).

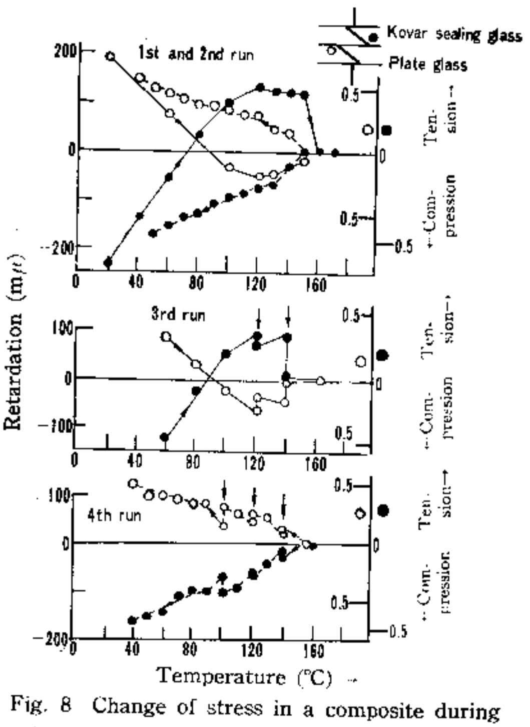

Fig. 8 Change of stress in a composite during temperature cycle. Arrows in the figure indicate soaking at various constant temperatures for 30 min.

put on a strip of plate glass. The stress in the strip was very small at room and high temperatures (Fig. 5).

3.4 *Change of stress during thermal cycle*

During the heating-cooling cycle, stresses at the central part of a fused silica-plate glass composite changed as shown in Fig. 6. Stresses at the part somewhat near the end changed as shown in Fig. 7. Although stresses were lower in the latter case, the temperature-stress relation was qualitatively the same.

The results on stresses in a plate glass-Kovar sealing glass composite during thermal cycle are shown in Fig. 8. Halfway in the cycle, effects of soaking at various constant temperatures were examined. Stresses were released during soaking. When temperature changed again, however, stresses increased rapidly and the effect of soaking disappeared.

4. Discussion

4.1 *Stress relaxation by the plasticity of indium*

Assume that glass strips with different thermal expansion coefficients are cemented together tightly and deformed elastically by bi-metallic action. When the Young's modulus E and the thickness of both glasses are equal the maximum stress at the cemented surface is expected to be (1/2~4/7) $\times E \times$(expansion difference δ)[1~3]. E is about 7×10^5 kg/cm² and the difference of expansion coefficient of the glasses is about $4\sim8\times10^{-7}$/°C. Then, δ's are $6.5\sim13\times10^{-4}$ between room temperature and the melting point of indium, and the maximum stress is calculated to be 270~540 kg/cm². Similarly, the change in maximum stress per 1°C is 2.8~5.6 kg/cm². Moreover, stress concentration near the ends of the composite is also expected.

In fact, however, stresses were almost zero at the ends and did not exceed 150 kg/cm² even at the central parts. These are far lower than the values calculated above. This is presumably due to the behavior of the indium layer.

The possible mechanism of stress relaxation by the layer is, for example, as follows: (1) It leads to slipping between the two glass strips, (2) Elastic deformation of the indium layer, though not distinct, decreases the stress in the composite and (3) Plastic flow of the indium layer caused by the thermal expansion difference between indium and the glasses releases the stress in the composite simultaneously.

As for the change in stress per 1°C, it was generally lower than the value calculated above, except in the case when the following conditions were all satisfied, namely: It was measured (1) at the central part of the composite, (2) at a temperature range considerably lower than the melting point of indium and (3) within a small temperature range in which the composite was heated after cooling or *vice versa*. This is also presumed to be due to the plastic behavior of the indium layer.

4.2 *Behaviors of indium layer*

To explain the experimental results described in 3. and 4.1, the following assumptions on the effects of the plasticity of the indium layer should be given, namely: (1) Stress at the free surface of indium is negligibly small, (2) In a composite, there is a limit in the difference of expansion between glasses or in the stress in glass strips which can be sustained by a unit width and length of the layer, (3) The expansion difference or stress above the limit is prevented to realize by the plastic flow of indium or the slipping between glass strips, (4) With increase of temperature, the limit tends to decrease, approaching quickly to zero near the melting point of indium, (5) By holding at constant temperature, the limit is lowered. The degree of lowering is slight at room temperature and is distinctly observable at high temperature, especially near the melting point of indium, and (6) If the indium layer deforms elastically, the compoite does so too. In particular, if the layer is sufficiently thin, the composite deforms following the theory of bi-metals approximately.

Temperature range in which indium layers deform elastically is, however, presumed to be considerably limited. The reason of this is as follows: Take a composite with no stress. With change of temperature, stress is generated by bi-metallic action. If all the materials deform elastically, stress concentration will take place near the ends of the composite, and at first the indium layer starts plastic deformation at these parts. With further change of temperature, the region of plastic deformation extends to the central part of the layer. As a result, the layer is presumed to deform elastically only within a limited range of temperature.

These presumptions seem to be reasonable in a sense. Strictly speaking, however, they should be assured by the theories of elasticity or plasticity in the future.

4.3 *Effect of the free surface of indium*

Let P_0 be the yield strength of indium and P_1, P_2 and P_3 be the three principal stresses in the layer. The condition of plastic yield of indium is

$$(P_1-P_2)^2+(P_2-P_3)^2+(P_3-P_1)^2=2P_0^2.$$

As indium is very soft, P_0 is low. The edges of the indium layer form free surfaces and the stresses perpendicular to the surfaces are zero. So the stresses in the other directions are lower than P_0 and the stresses in glass strips caused by the layer are also low. This is an explanation of the lowering of stress near the ends of a composite (Fig. 3). In a glass strip coated with a thin layer of indium, the free surface of indium is widely exposed, and the stress in the strip cannot be high (Fig. 5).

4.4 *Stress distribution in a composite*

The indium layer has free surfaces not only at its short edges but also along its long edges. Accordingly, the maximum stresses in the layer are limited by both width and length of the layer and by P_0. This means that the bending moment in the composite or the expansion difference between two glass strips sustained by a unit length of the layer is also limited. Stresses in the composite correspond approximately to integrals of the values along the length of the layer on one hand, and on the other hand, they are restricted by the condition that at the ends the stresses should be nearly zero. Consequently, the stress distribution has a maximum at the central part of the composite (Fig. 3).

It is expected that the longer the composite, the higher is the maximum stress in it. In an extremely long composite, however, stress is expected not to exceed the value of a glass-to-glass direct seal without an indium layer.

4.5 *Behavior of indium layer during cooling*

Suppose that two glass strips with different thermal expansion coefficients are cemented by an indium layer. When the composite is cooled from above the melting point of indum (point M in Fig. 9), indium solidifies at M and stress is generated in the composite. If the indium layer is thin and deforms elastically, the stress is equal to that calculated by the theory of bi-metals (MA). Actually, however, plastic flow or creep in the layer is distinct near M and stress is released considerably and becomes less than MA (MB).

The lower the temperature, the higher are

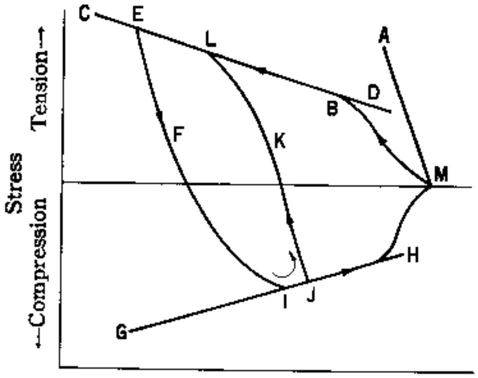

Fig. 9 Schematic explanation of temperature-stress characteristics of bi-metallic composite.

the limiting values of stress determined by P_0 (represented by CD and GH in Fig. 9). When the stress reaches the line CD, generation of a higher stress is prevented by the plastic flow in the indium layer and the stress then changes along the line CD (Fig. 9).

4.6 *Change of stress during heating*

Suppose a composite cools to the temperature represented by point E in Fig. 9. When heated, the expansion difference between glass strips and stress in the composite begin to decrease. Stress in the indium layer also decreases and becomes a value lower than P_0, and it behaves elastically. Accordingly, the composite deforms elastically and the stress in it changes in parallel with the line MA (EF).

As the deformaion of the composite proceeds, however, concentrated stress is generated first at the ends of the composite and the indium layer begins to flow. This corresponds to the point F. The region of plastic deformation extends gradually to the central part of the composite, and the stress departs from the extension of the line EF. The stress reaches zero and there reverses its sign. When the stress reaches the line GH at point I, the whole region of the indium layer deforms plastically, and thereafter, the stress changes along the line GH. With further increase of temperature to M, the stress decreases gradually and then quickly reaches zero near the point M. These processes are represented in Figs. 7 and 8 experimentally.

4.7 *Change of stress during thermal cycle*

By analogy with the cases discussed in **4.5** and **4.6**, change of stress in a composite during thermal cycle can be forecast. When the composite is heated to the point J in Fig. 9, for example, and then subjected to cooling, the stress changes following the path JKL. This process is shown in Figs. 6 and 7.

4.8 *Effect of soaking at various constant temperatures*

When a composite is held at a relatively high temperature, stress in the composite decreases in some degree by the creep of the indium layer (PQ or RS in Fig. 10), and the stress in the layer becomes lower than P_0. With further change of temperature, the layer deforms elastically, and the stress in the composite runs in parallel with the line MA (QT or SU). The stress, however, soon reaches the line CD or GH and after that the processes are similar to those discussed in 4.-5, 7. Soaking at constant temperatures has hardly any effect on the amount of stress at room temperature.

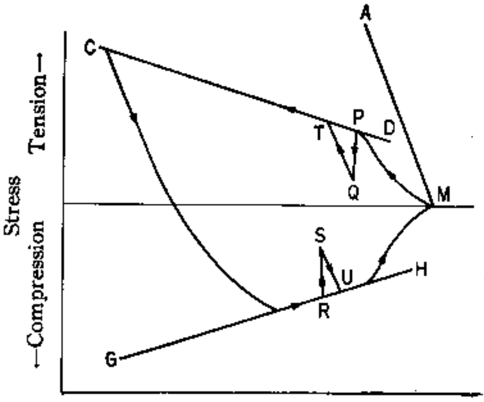

Fig. 10 Schematic explanation of effects of soaking at various constant temperatures.

4.9 *Factors which affect stresses in composite*

As described above, the stress in a composite is determined firstly by the yield strength or thickness of indium, and secondly by the dimensions or stiffness of glasses to be cemented. The larger the dimensions of the composite, the higher is the maximum stress attainable in a composite, and suitable stiffness of glass components is necessary.

5. Conclusion

(Refer to the abstract.)

References

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