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STRESSES ARISING IN GLASS-TO-METAL BEAD SEALS IN THE COURSE OF ANNEALING

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It was found that calculation of stresses arising in a bead seal can be simplified by computing the stresses in two equivalent sandwich seals. Equations for the calculation of stresses in the glass element of the seal are derived. A good agreement between the experimental and computed temperature dependence of the stresses was found.

INTRODUCTION

The extensive stresses, which can arise in glass during annealing, are the main cause of failures in glass-to-metal joints in electrical vacuum devices. The stress values can be strongly influenced by changes in the temperature-time conditions of the seal annealing schedules. The experimental trial-and-error method is quite often ineffective because of the great number of possible variations involved. A rational choice of the annealing schedule for glass-to-metal seals should be based on a mathematical analysis of the stresses arising in the glass element of the seal.

Structural and mechanical relaxation in the glass element of a seal [1], [2] is an important factor determining the stresses in glass-to-metal seals. The fractional exponent, proposed by Kohlrausch [3], is often applied in the description of relaxation processes in glass. Numerous experimental data show that glass is a linear viscoelastic material (see e.g. [4]). The relaxation processes become too complex when the temperature and the fictive temperature of glass seal element vary, so that it is advisable to use an electronic computer to predict the results of annealing

THEORETICAL

Sandwich (Fig. 1a) and bead (Fig. 1b) seals are often used as a base for the evaluation of stresses in glass-to-metal joints of electronic devices (see e.g. [2], [5]). The algorithm of stress calculation in a sandwich seal during its annealing according to a given temperature-time schedule, derived in [6] (also refer to [2]) includes: 1. computing the fictive temperature of glass, its viscosity and dilatometric length; 2. calculating the stresses depending on the difference between the thermal expansion of glass and metal and on the rate of stress relaxation. The uniformity of the state of stress in the glass layer of the sandwich allowed to use a simple algorithm, based on computing the so-called free size [1], [2], [6] of the glass component.

It is far more difficult to use an algorithm of this type for a bead seal, as this is characterized by different values of radial σ_r, tangential σ_Θ and axial σ_z stresses. In addition to this, σ_r and σ_Θ are variable along the radius of the seal. Application of the algorithm, based on computing the "free sizes" of the glass element in three directions, would require the glass element to be divided into several layers.

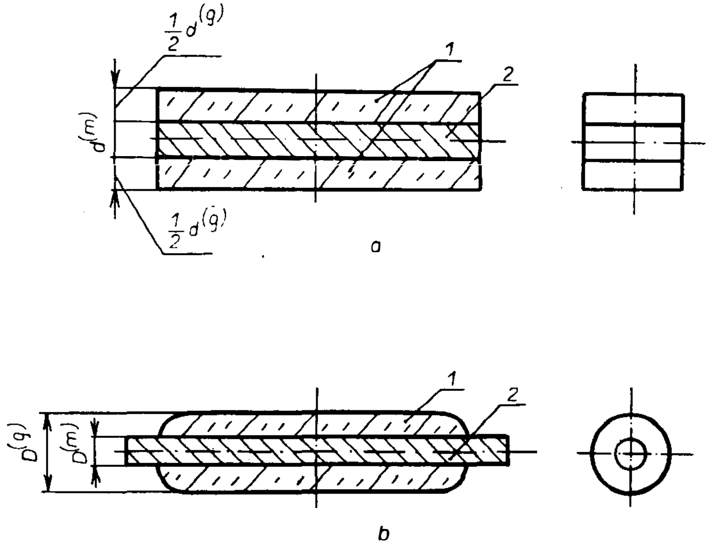

Fig. 1. The types of glass-to-metal seals;
a — sandwich seal, b — bead seal; 1 — glass, 2 — metal.

A visco-elasticity analysis for a bead seal was presented in [7]. However, the equations obtained appear to be too complex. This can hamper the use of the respective algorithm by other investigators and the application of the method for the analysis of stresses in more complex glass-to-metal seals.

To simplify the calculations one can use the idea that the stresses in a bead seal relax similarly to those in the sandwich seal which has the same rigidity ratio. This assumption was utilized in [2] for very rough approximations. Below it will be shown how the idea can be employed to develop an effective and sufficiently precise method for stress calculation in glass-to-metal bead seals.

To determine the stresses in a bead seal, the principle of correspondence of the elastic and visco-elastic problems was used [8], [9]. This principle was applied to the solution adduced in [9]. With regard to this, the Laplace transforms of functions of radial $\sigma_r(t)$, tangential $\sigma_\Theta\,(t)$ and axial $\sigma_z\,(t)$ stresses (where t is time) may be represented as follows:

$$\sigma_r^*\,(S) = \int\limits_0^\infty \sigma_r\,(t)\,\mathrm{e}^{-st}\,\mathrm{d}t = \left[1 - \left(\frac{D^{(g)}}{2r}\right)^2\right] \sigma_1\,(S),$$

$$\sigma_\Theta^*\,(S) = \left[1 + \left(\frac{D^{(g)}}{2r}\right)^2\right] \sigma_1\,(S),$$

$$\sigma_z^*\,(S) = \sigma_2\,(S) + 2\nu\sigma_1^*\,(S),$$

where

$$\sigma_1\,(S) = \frac{E^{(g)}}{2 - 2\nu + \beta}\;\frac{R^*(S)\;\Delta L^*(S)S}{1 + \dfrac{1 - 2\nu}{2 - 2\nu + \beta}\,\dfrac{E^{(g)}}{E^{(m)}}\,R^*(S)S}\,, \tag{1}$$

$$\sigma_2\ (S) = E^{(g)} \frac{R^*(S)\ \Delta L^*(S)S}{1 + \frac{E^{(g)}}{E^{(m)}} \beta R^*(S)S}, \tag{2}$$

$E^{(g)}$, $E^{(m)}$ are modul of elasticity of the glass and the metal respectively,
ν is Poisson's ratio, which is considered constant for the glass and assumed to be the same for both elements of the bead seal,
r is the distance between the axis of the seal and the point at which the stresses are calculated,
S is a complex variable,
$E^{(g)}R(t)$ is the relaxation function of the glass,
$\Delta L(t)$ is the difference of the dilatometric changes in length of the metal and glass elements,

$$\beta = \left(\frac{D^{(g)}}{D^{(m)}}\right)^2 - 1,$$

$D^{(g)}$, $D^{(m)}$ are the diameters of the seal and the metal elements respectively (cf. Fig. 1b).

The Laplace transform of the function of stresses in a sandwich seal $\sigma(t)$, whose parameters are equal to $E_e^{(g)}$, $E_e^{(m)}$, $d_e^{(g)}$, $d_e^{(m)}$, ν_e (cf. Fig. 1a) may be written in the following form:

$$\sigma^*(S) = \frac{E_e^{(g)}}{1 - \nu_e} \frac{R^*(S)\ \Delta L^*(S)S}{1 + \frac{E_e^{(g)}d_e^{(g)}}{E_e^{(m)}d_e^{(m)}} R^*(S)S}. \tag{3}$$

On comparing the equations (1), (2) and (3), one can draw the conclusion that in order to determine the stresses in a bead seal it is sufficient to calculate stresses $\sigma_1(t)$ and $\sigma_2(t)$ in two equivalent sandwich seals. The parameters of these equivalent selas $E_{e,1}^{(g)}$, $E_{e,2}^{(g)}$, $E_{e,1}^{(m)}$, $E_{e,2}^{(m)}$, $d_{e,1}^{(g)}$, $d_{e,2}^{(g)}$, $d_{e,1}^{(m)}$, $d_{e,2}^{(m)}$, $\nu_{e,1}$, $\nu_{e,2}$ must satisfy the following equations:

$$E_{e,1}^{(g)} = \frac{E^{(g)}}{2 - 2\nu + \beta}, \quad E_{e,2}^{(g)} = E^{(g)},\ E_{e,1}^{(m)} = E_{e,2}^{(m)} = E^{(m)},$$

$$\frac{d_{e,1}^{(g)}}{d_{e,1}^{(m)}} = (1 - 2\nu)\beta, \quad \frac{d_{e,2}^{(g)}}{d_{e,2}^{(m)}} = \beta, \quad \nu_{e,1} = \nu_{e,2} = 0.$$

When $D^{(g)}/D^{(m)} \geq 4$, the term $2\nu\sigma_1(t)$ can be neglected in practical calculations while maintaining a sufficient accuracy. In this instance the calculation of the axial stresses is restricted to that described in [2].

RESULTS AND CONCLUSION

The relationships obtained by the method suggested conform well to known experimental data. These data include all the results presented in [7]. Of special interest is the case when in the heated seal the sign of σ_z remains the same but that of the difference $\sigma_\Theta - \sigma_r$ changes at a certain temperature (cf. [2], where the experimental results by I. N. Dulkina were presented). This experimental fact demonstrates clearly that a purely elastic analysis is incapable of providing even a qualitative agreement between calculations and experimental data. Unfortunately, this particular case was not analysed by the authors of [7]. We have chosen it to illustrate the validity of our method.

Fig. 2 shows the experimental data [2], obtained by measuring the stresses in a bead seal by means of the photoelasticity method. The diagram clearly shows the variation of stresses σ_z (a) and the difference $\sigma_\Theta - \sigma_r$ (b) arising in the course of

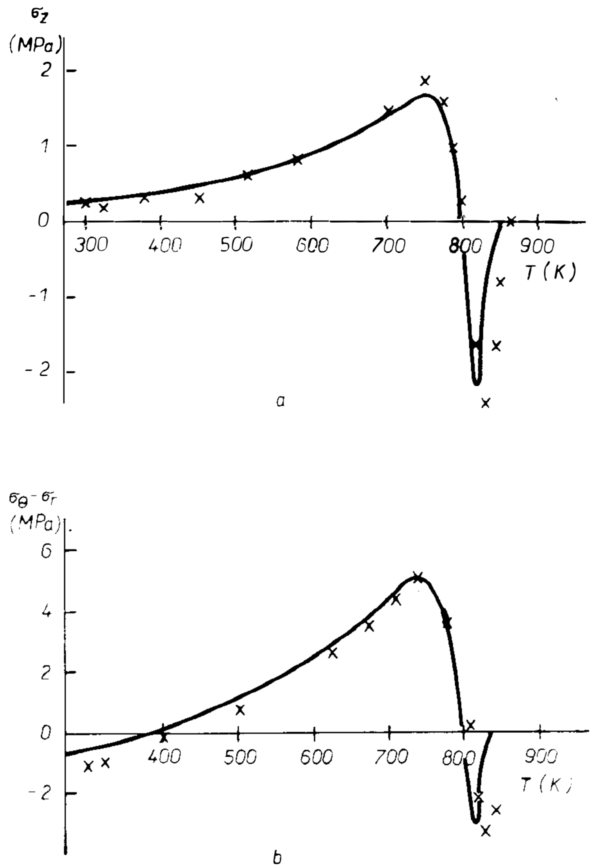

Fig. 2. Experimental (×) and calculated (—) dependences of stresses in glass during the heating of a bead seal of borosilicate glass with molybdenum, which has been previously subjected to isothermal holding at 788 K for 3 hours; the rate of temperature changes during cooling and heating was 3 K per minute;
$D^{(g)}/D^{(m)} = 4$;
a: σ_z; b; $\sigma_\Theta - \sigma_r$ *for* $r = 0.62D^{(m)}$.

heating of a seal which has previously been subjected to an isothermal hold at 788 K. The necessary characteristics of the seal elements were taken over from [2] (these characteristics were also used in [7]). The results of the calculations are plotted as full lines. The calculated dependences conform well to the experimental data, so that the assumptions taken in the present paper may be considered to be correct.

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VÝPOČET PNUTÍ, VZNIKAJÍCÍHO PŘI CHLAZENÍ SPOJE MEZI SKLEM A KOVEM V PERLE

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Bylo zjištěno, že výpočet pnutí v perle může být zjednodušen tím, že je převeden na stanovené pnutí ve dvou ekvivalentních sendvičových spojích. Byly odvozeny vztahy pro výpočet pnutí v ekvivalentních spojích. Vypočítané hodnoty dobře souhlasí s experimentálními výsledky.

Obr. 1. Typy spojů mezi sklem a kovem; a — sendvičový spoj, b — perlový spoj, 1 — sklo, 2 — kov.
Obr. 2. Experimentálně stanovená (×) *a vypočítaná* (—) *závislost pnutí ve skle v průběhu zahřívání perlového spoje boritokřemičitého skla s molybdenem. Spoj byl chlazen izotermní výdrží při teplotě 788 K 3 hodiny, rychlost teplotní změny během chladnutí a zahřívání činila 3 K za minutu;*
$D^{(g)}/D^{(m)} = 4$;
a; σ_z, b: $\sigma_\Theta - \sigma_r$ při $r = 0{,}62D^{(m)}$.

РАСЧЕТ НАПРЯЖЕНИЙ, ВОЗНИКАЮЩИХ ПРИ ОТЖИГЕ БУСИНКОВЫХ СПАЕВ СТЕКЛА С МЕТАЛЛОМ

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Установлено, что расчет напряжений в бусинковых спаях может быть упрощен сведением его к определению напряжений в двух эквивалентных сэндвичевых спаях. Получены формулы для вычисления параметров эквивалентных спаев. Расчеты по предложенной методике хорошо согласуются с известными экспериментальными данными.

Рис. 1. Типы спаев стекла с металлом: а — сэндвичевый спай, б — бусинковый спай; 1 — стекло, 2 — металл.
Рис. 2. Экспериментальные (x) *и расчетные* (—) *зависимости напряжений в стекле при нагревании бусинкового спая боросиликатного стекла с молибденом, который на стадии охлаждения подвергался изотермической выдержке при 788 K в течение 3 часов; скорость изменения температуры при охлаждении и нагревании составляла 3 K/мин;*
$D^{(g)}/D^{(m)} = 4$;
a : σ_z; b : $\sigma_\Theta - \sigma_r$ при $r = 0{,}62D^{(m)}$.