Paper

Finite-Element Stress Analysis and Strength Evaluation of Super High Pressure Mercury Lamp Bulbs under Internal Pressure

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ABSTRACT

Super high pressure mercury discharge lamps have been used as UV light sources for photolithography, such as patterning LCDs, PCBs and semiconductors. The bulbs of the lamps are generally made of silica glass. This study evaluates optimal shapes for various lamp bulbs under internal pressure employing the Finite Element Method(FEM). As the result, the optimal shape of the bulb was obtained and the relationship between the rupture stress and the bulb wall thickness t was clarified. The optimal shape of the bulb obtained is $0.7 \leq D/L \leq 0.85$, where L is the total length of the bulb and D is the diameter. Static water pressure-tests were conducted in order to verify the numerical results. It was found that tendency between the numerical results and experiments were in fairly good agreement.

KEYWORDS: super high pressure mercury vapor lamp, lamp bulb, tensile strength under internal pressure, optimal shape of lamp

1. Introduction

Super high pressure mercury discharge lamps have been used as UV light sources in photolithography exposure process such as patterning liquid crystal displays, semiconductors and printed electric boards. It has been well known that the internal pressure of the lamps is more than 1.0MPa and the bulb outer surface temperature is more than 500°C under their operations. Thus the rupture of the lamps is one of the most important problems and it can be assumed that the internal pressure is one of the most dominant factors for the rupture. If the lamps rupture under operations, It can be assumed that the expensive parts in the optical system such as mirrors, lens and optical filters are damaged or destroyed by the ruptured pieces of the bulb and the mercury which is enclosed in the bulb will be scattered. Moreover, it can be speculated that long time and a lot of expenses will be needed for repairing the optical systems and then manufacturing facilities lines must be stopped. Thus, pressure resistance of the lamps under internal pressure must be needed and examined carefully.

However, only few studies had been done on the optimal design of the lamps. Thouret had studied on the optimal shape of the bulb under internal pressure and thermal loading using the numerical methods¹⁾.

Recently, input power of the lamps and their bulb sizes have been increased as the patterning area sizes

in the photolithography process are increased. Thus it is necessary to investigate on the optimal shape of bulbs under internal pressure.

The bulb size and shapes have been generally designed according to the following processes; (1) The bulb internal surface area S must be determined such that working temperature of the bulbs does not reach the strain point of silica glass (about 1100°C²⁾). (2) The inner surface area S is determined from the ratio of input power P_I to the bulb internal surface area S , while the ratio P_I/S has been determined previously from the obtained experimental data. (3) The bulb total length L , the bulb wall thickness t , and the bulb outer diameter D have been decided empirically. Thus, it has not been made clear that whether the safety of the bulb shape is enough or not under internal pressure. Moreover, it is necessary to investigate the rupture characteristics and the optimal shapes of the bulb under internal pressure. The objective of this study is to investigate the optimal bulb shape under internal pressure and to demonstrate a safety guide line for a reliable bulb design.

2. Experimental and Finite-Element Methods

2.1 The lamp construction

Figure 1 shows the schema of the lamp construction. A pair of electrodes are in the lamp. Arc discharge is occurred between the electrodes and light is radiated

Figure 1 Schematic of the lamp

from the arc discharge in operation. The spectrums of the light have strong intensity between UV and visible wave length because the rare gases (such as Helium, Xenon, and Argon) and mercury is enclosed in the bulb. Generally, the lamps can be consisted of three parts described as follows.

(1) The Bulb

It is well known that the bulb internal pressure P is more than 1.0 MPa and temperature of the bulb outer surface is more than 500°C under operation mentioned before. The bulbs are generally made of silica glass because the silica glass is one of materials with the lowest linear thermal expansion coefficient. Furthermore, the silica glass has good optical penetrating characteristics between visible and UV wave lengths. As mentioned above, the bulb size has been increased. Recently, the outer diameter of some lamp bulbs exceeds 100mm while the wall thickness t still remains 4mm approximately.

(2) The Sealed Parts

The sealed parts are made of silica glass parts, metal parts and extremely thin some sheets of molybdenum foils. The glass and metal parts are mounted each other and they are sealed inside of the sealing glass in their manufacturing processes.

(3) The Metal Bases

The metal bases are connected to the end of the sealed parts in order to fix the lamps in the optical systems and turn on the electrification from power supplies.

The lamps are generally fixed vertically in optical systems while the lamp is described horizontally as shown in Fig 1. They are generally used with direct current in their operations.

2.2 Finite element calculations

2.2.1 Procedure of the FEM calculations

The employed calculation process are described as follows.

- (1) The maximum principal stress σ_1 distribution in the bulb under internal pressure is obtained by finite-element method (FEM) calculations because it is well known that glass material is one of the typical brittle materials at room temperatures and rupture

Figure 2 Schematics of actual lamps and model for FEM calculations

of the brittle materials is generally explained due to the maximum principal stress theory³⁾.

- (2) Optimal shape of the bulbs is investigated under the condition that the inside surface area S [mm²] is held constant. The radius R of the curvature of the bulbs is varied in order to change the total length L [mm] and outer diameter D [mm] of the bulbs. The optimal shape of the bulbs is defined such that the maximum principal stress σ_1 in the bulb becomes minimal and it tends to distribute more uniformly.
- (3) The similarity of the ratio D/L is investigated by changing the value S .
- (4) The relationship between the internal pressure P and the maximum value of maximum principal stress $\sigma_{1\max}$ is examined.
- (5) The rupture stress of the silica glass is compared with the calculated maximum value of maximum principal stress $\sigma_{1\max}$.
- (6) The relationship between the wall thickness of the bulb t [mm] and the maximum value of maximum principal stress $\sigma_{1\max}$ under internal pressure is examined.
- (7) Finally, the optimal shape of the bulbs under internal pressure is discussed.

2.2.2 Conditions in FEM calculations

Figure 2 shows a schematic model for FEM calculations while an actual lamp is also described. The bulb part in the lamps shown in Fig 2 is analyzed for reducing the time of FEM calculations. The one-fourth of the bulb is analyzed in FEM taking into account the bulb symmetry. Figure 3 shows an example of mesh division in the FEM model. The numbers of nodes employed were between 6400 and 6500 and those of the elements were from 4500 to 5000 in the FEM calculations.

The effect of thermal stress and peculiar stress concentration factors in the glass such as micro cracks and local flaws⁴⁾ are not taken into consideration.

Figure 3 An example of mesh divisions in FEM calculations
(Nodes: 6436, Elements: 4880)

Figure 4 Dimensions of the bulb

local flaws⁴⁾ are not taken into consideration. Moreover temperature of the bulb model was assumed to be 20°C (room temperature).

Young's modulus and Poisson's ratio of silica glass at 20°C were 73.1 GPa and 0.17 respectively²⁾ and the values were employed in the FEM calculations.

It is well known that the silica glass is a brittle material⁵⁾ when the temperature is less than the annealing point²⁾ (about 1200°C). Thus, Young's modulus was held constant as the value as mentioned above in the FEM calculations.

Equations (1) and (2) show the relationship among the dimensions in the bulbs, where S is the bulb inner surface area, L is the total bulb length, R is the curvature radius, D is the outer diameter, ψ is the outer diameter of the sealing glass, and t is the wall thickness as shown in Fig 4. The equations (1) and (2) are obtained in order to investigate the effect of the bulb dimensions.

$$S = 4\pi \cdot (R - t) \left\{ L/2 \cdot (1 - t/R) - (R - D/2) \cdot \sin^{-1}(L/2R) \right\} \quad \cdots (1)$$

$$R \cdot \cos(\sin^{-1}(L/2R)) - (R - D/2) = \psi/2 \quad \cdots (2)$$

2.3 Experimental Method

Figure 5 shows the schema of the static water pressure tests⁶⁾. The actual three lamps were used as the specimens in the water pressure tests. The bulb outer diameter D was 105 mm, the total length L as 136 mm, the wall thickness t as 3.5 mm, the outer diameter of the sealing glass as 39 mm, and the bulb inner surface area S as 36100 mm². The inner surface area S was obtained from Eq.(1).

Figure 5 Schematic of the water pressure test

Figure 6 Schematic of measuring method for the bulb outer strain in the water pressure test

In the experimental system, the static water pressure test machine DDT-111W (made by Daiich Kagaku Co., Ltd.) was employed for pressurizing the specimens. The specimens had been pressurized in the water filled glass aquarium in order to prevent scattering broken lamp pieces. The specimens were connected to the test machine through a glass tube as shown in Fig.5. It is well known that the lamp pressurizing test has been employed to investigate the pressure resistance^{1),7)} and gas was used for pressurizing the specimens. Thus, it is assumed as a problem that the broken pieces of the lamps scatter with high velocity and they were broken by secondary collisions when the gas was used because inflation ratio of the gas is much higher than that of water. Thus, it can be assumed that assemble process of the broken pieces and investigating on a point where the rupture occurred could be much more difficult in gas pressure test than in the water pressure tests.

Figure 6 shows the positions of glued strain gauges for

measuring the strain on the outer bulb under internal pressure. The strains on the outer surface of the bulb were directly measured at the three points by six strain gauges. Two-direction gauges were used in the experiment and their gauge length was 1 mm. The obtained strains by the strain gauges were changed into the stress values with Young's modulus as mentioned in above (2.2.2). The calculated maximum principal stress σ_1 obtained by FEM cannot be compared with the stress obtained from measured strain at the bulb outer surface. However, the tendency of stress distribution at the bulb outer surface obtained by FEM can be compared with the stress obtained by the measured strains when the bulb was pressurized. In addition, it is easy to know that the direction of the stress because two-direction strain at the bulb outer surface is measured by the strain gauges.

Table 1 Calculated length L and outer diameter D when inner surface area S is held constant as 19590mm^2

Outer diameter D (mm)	Length L (mm)	Ratio D/L
70	120.69	0.58
76	108.57	0.70
80	100.59	0.80
84	98.82	0.85
88	93.82	0.938

3. Comparisons between Numerical and Experimental Results and Consideration

3.1 Results of the FEM calculations

3.1.1 Maximum principal stress σ_1 distribution when bulb surface area was held constant

As mentioned in introduction, the inner surface area S of the bulbs is generally held constant in the design of bulb shape. Thus the maximum principal stress σ_1 distribution was calculated when the surface area S was held constants as 19590mm^2 . Moreover, the bulb wall

Figure 7.1 Relationship between position of x and maximum principal stress in the bulb under 3.0 MPa internal pressure

Figure 7.2 Maximum principal stress distribution in the bulb as contours under 3.0 MPa internal pressure

thickness t was held constant as 3.5mm and the outer diameter of the sealing glass ψ as 34mm.

Table 1 shows the calculated total length L [mm], the outer diameter D [mm] and the ratio D/L . The values L and D were calculated from Eqs. (1) and (2).

Figure 7.1 shows the values of the maximum principal stress σ_1 . Figure 7.2 shows the maximum principal stress distribution described as contours. The color charts in Fig. 7.2 represent the intensity of the maximum principal stress σ_1 for each outer diameter. The bulb shape was varied as shown in Table 1. The abscissa in Fig. 7.1 represents the X -axis positions and the origin of the X -axis is denoted by O. The ordinate is the maximum principal stress σ_1 . It was found that all of the calculated maximum principal stress σ_1 were positive at the elements. Thus, the maximum principal stress σ_1 value is tensile when the bulb is subjected to internal pressure. Moreover, it is observed that the position where the maximum value of maximum principal stress $\sigma_{1\max}$ is occurred is close to the center of the bulb when the ratio D/L of the outer diameter D [mm] to the total length of the bulb L [mm] is less than 0.75. However, the position where the maximum value of σ_1 is occurred is near the bulb end when the ratio D/L is more than 0.75.

According to the numerical results, the optimal relationship D/L under internal pressure was found to be $0.7 \leq D/L \leq 0.85$ because the maximum value of maximum principal stress $\sigma_{1\max}$ was minimum. The tendency of these results was the same as the hollow cylinders under internal pressure obtained from the theory of elasticity³⁾.

3.1.2 Relationship between D/L in optimal shapes and inner surface areas

Figure 8 shows the relationship between the obtained ratio D/L in the optimal bulb shape under internal pressure described in paragraph 3.1.1 and the maximum value of the maximum principal stress $\sigma_{1\max}$. It was found that the maximum values of the maximum principal stress σ_1 were decreased as the bulb inner surface area S [mm²] was decreased. Thus it can be assumed that the pressure resistance of the bulbs is increased as the bulb inner surface is decreased.

Table 2 shows the bulb inner surface area S [mm²], the outer diameter D [mm], the total length L [mm], and the outer diameter of the sealing glass ψ [mm] when the bulb shapes are optimal under internal pressure. The bulb wall thickness t is held constant at 3.5mm in the FEM calculations.

As the result, it is found that the ratio D/L is $0.75 \leq D/L \leq 0.85$ when the bulb shapes are optimal. Moreover, it can be assumed that the bulb optimal shape under internal pressure is not influenced by the inner surface area S .

Figure 8 Relationship between the ratio of the outer diameter D to the total length L D/L and the maximum value of maximum principal stress $\sigma_{1\max}$

Table 2 Relationship between the bulb inner surface area and the dimensions determined as the optimal shapes

Inner surface area S (mm ²)	19600	36100	60500
Length L (mm)	100	134	163
Outer diameter D (mm)	80	106	140
Outer diameter of sealing glass ϕ (mm)	34	39	39
The ratio D/L	0.8	0.79	0.85

Figure 9 Relationship between the internal pressure P and the maximum value of maximum principal stress $\sigma_{1\max}$ when the bulb inner surface area S was held constant ($S=19590, 36800$ and 46170 mm²)

3.1.3 Effect of the inner surface area S on the maximum value of the maximum principal stress σ_1 value

Figure 9 shows the relationship between the internal pressure P [MPa] and the maximum value of the maximum principal stress $\sigma_{1\max}$ in the optimal shape bulbs as shown in Table 2. A horizontal dotted line

Figure 10 Relationship between the internal pressure P and the maximum value of maximum principal stress $\sigma_{1\max}$ when the bulb wall thickness t was varied

Figure 11 Relationship between the internal pressure P and the stress at the outer surface of the bulb in the water pressure test

near the value of 60MPa in Fig. 7 represents the rupture stress of silica glass at 20°C⁽²⁾.

As the result, it was found that (1) the maximum value of the maximum principal stress $\sigma_{1\max}$ was increased linearly as the Internal pressure P was increased, (2) the gradient in the three stress lines shown in Fig. 7 is increased as the inner surfaces S is increased.

Moreover, it is found from Fig. 9 that the rupture pressure of the bulb as shown in Table 2 is more than 5.0MPa.

3.1.4 Relationship between the bulb wall thickness t and maximum value of the maximum principal stress σ_1

Figure 10 shows the relationship between the internal pressure P [MPa] and the maximum value of the maximum principal stress $\sigma_{1\max}$ when the bulb inner surface S is held constant at 36100mm², the total length L at 136 mm, the bulb outer diameter D at 105mm, and the bulb wall thickness t was changed from 2.5mm to 5.0mm. It

Figure 12 An example of ruptured specimens

Table 3 Ruptured pressure and positions of the specimens

Specimen No.	Ruptured Pressure(MPa)	Ruptured position
1	3.52	Sealed parts of the Cathode side
2	4.01	
3	3.60	

was found that the maximum value of the maximum principal stress $\sigma_{1\max}$ was decreased as the bulb wall thickness t was increased. Thus it can be assumed that the pressure resistance of the bulbs is increased as the wall thickness t is increased. The effect of the wall thickness t on the safety design of the bulb must be investigated. In section 3.4 the effect is examined.

3.2 Experimental results and comparison between the numerical and the experimental results

3.2.1 Stress measurement of the outer surface of bulbs by strain gauge

Figure 11 shows the relationship between the internal pressure and the calculated stress value obtained from the measured strain values at the outer surface of the bulb. the Y direction represents the circumference (outer diameter) direction of the bulb as shown in Fig. 5.

It was found that (1) both the stresses in the X and Y directions were increased as the internal pressure was increased, (2) the stress intensity at the bulb center was greater than that at the bulb end, (3) each direction of the stress was tensile when the internal pressure was more than 0.5MPa, (4) the stress intensity in the Y direction was greater than that in the X direction.

3.2.2 Rupture pressure of the specimens

Figure 12 shows an example of the ruptured specimens. It was found that all specimens ruptured from the end of the bonded area between molybdenum foils and silica glass in the sealed parts as shown in Fig. 1. Table 3 shows the ruptured pressure and ruptured position of

Figure 13 Comparison of the stress distribution at the bulb outer surface between the obtained stress in the water pressure test and the calculated maximum principal stress σ_1 in the numerical method

the specimens. It was found that the ruptured pressure of the specimens were between 3.5 and 4.0MPa and all specimens were ruptured from the cathode side.

3.3 Comparison between the experimental and numerical results

Figure 13 shows the relationship between the X -axis position and the stresses values. The origin of the X -axis is denoted by O. The intensity of maximum principal stress σ_1 obtained from the FEM calculations is compared with the stress intensity obtained from the experiments. From the comparisons, the following results are obtained.

- (1) The stress intensity of the bulb center was greater than that of the bulb ends.
- (2) The stress value increased as the internal pressure increased.
- (3) The direction of the stresses was tensile.

Thus, the tendency of the numerical results was in a fairly good agreement with the experimental results.

3.4 Consideration

The optimal shape of the bulb under internal pressure was obtained from the above results as follows.

- (1) The maximum value of maximum principal stress became minimal when the ratio of the bulb diameter D to the bulb length L was $0.7 < D/L < 0.85$.
- (2) The maximum value of maximum principal stress was increased as the bulb wall thickness t was decreased.
- (3) The maximum value of maximum principal stress was increased as the bulb inner surface S was increased when the bulb wall thickness t was held constant.

It was clarified that the pressure resistance of the bulb was increased as the bulb wall thickness t was increased. However, it was also found that the bulb

Figure 14 Relationship between the bulb wall thickness t and the ratio $\sigma_{1\max}$ to the internal pressure P

Figure 15 Relationship between the bulb wall thickness and the estimated rupture pressure of the bulb

temperature in operation was increased as the bulb wall thickness t was increased. Thus it is necessary to estimate the rupture pressure of the bulb when the bulb wall thickness t was varied and to establish a guideline for safety design of the bulbs.

Figure 14 shows the relationship between the bulb wall thickness t and the ratio $\sigma_{1\max}/P$ of the maximum value of the maximum principal stress $\sigma_{1\max}$ to the internal pressure P when the inner surface area of the bulb S is held constant at 19590mm², 36800mm², or 46170mm² respectively. In Fig.14, the dotted lines and the equations represent the approximation curves for the calculated results which are obtained using the least square method. It can be assumed from the equations that the value of the ratio $\sigma_{1\max}/P$ varies in inverse proportion to the thickness of the bulb wall t as shown in Eq.(3).

$$\frac{\sigma_{1\max}}{P} = \frac{\text{const}}{t} \quad \text{..... (3)}$$

Figure 15 shows the relationship between the bulb wall thickness t and the estimated rupture internal

pressure P when the inner surface area of the bulb S is held constant at 19590 mm², 36800 mm² or 46170 mm² respectively. The rupture pressure of the bulbs is estimated from the rupture stress of silica glass at 20°C²⁾ (about 60 MPa). It was found that the estimated rupture pressure of the bulbs increased linearly as the bulb wall thickness t increased and the gradient of the linear lines shown in Fig.15 was increased as the bulb inner surfaces S was decreased.

As mentioned above, the relationship between the rupture pressure of the bulbs and the wall thickness t can be obtained. Thus, it is necessary to examine the effect of the bulb thickness on the safety for the bulb rupture in actual design. The pressure resistance of the bulbs tended to be decreased as the inner surface area was increased when the bulb thickness t was held constant. Therefore, in designing the bulbs the thickness t should be decided due to the estimated rupture pressure in this study.

4. Conclusions

In this study, the pressure resistance of the bulbs in super high pressure mercury discharge lamps under internal pressure was investigated experimentally and numerically when the bulb wall thickness t , outer diameter D , total length L , inner surface area S , and outer diameter D of the bulbs were varied. The results obtained are summarized as follows.

- (1) The position where the maximum value of maximum principal stress was occurred was near the center of the bulbs when the ratio D/L of the outer diameter D [mm] to the length of the bulb L [mm] was less than 0.75. However, the position was near the bulb end when the ratio D/L was more than 0.75.
- (2) The pressure resistance of the bulb is the highest when the ratio of the bulb outer diameter D to the length L was $0.7 < D/L < 0.85$.
- (3) The effect of the wall thickness t on the bulb rupture

was examined by the finite element calculations. It was found that the rupture pressure of the bulb was increased as the bulb wall thickness t was increased and pressure resistance of the bulbs were decreased as the inner surface areas were increased when the bulb wall thickness t was held constant.

- (4) The stress distribution at the outer bulb surface was investigated experimentally in the water pressure test. As the result, it was found that the stress intensity was increased as the internal pressure was increased. Furthermore, it was also found that the stress intensity at the bulb center was larger than that at the bulb end.
- (5) It was observed that the rupture of the lamps was occurred from their sealed parts in the water pressure test.

In near future, the authors will investigate on the rupture of sealed parts. Furthermore, the authors have been studying about effect of thermal stress and residual stress on the rupture of the lamps.

References

- (1) W. E. Thouret : Tensile and thermal stress in the envelope of high brightness high pressure discharge lamps, *Illu. Eng.*, pp.295-302 (1960).
- (2) N. P. Bansal and R. H. Doremus : Handbook of glass properties, pp.7-30, Academic Press (1986).
- (3) S. P. Timoshenko and J. N. Goodier : Theory of elasticity, pp. 221-225, McGraw-Hill (1985).
- (4) A.A. Griffith : The phenomena of rupture and flow in solids, *Phil. Trans. R. Soc. Lond.*, A221, 163 (1920).
- (5) T. Sawa : Sainyumon Zairyourikigaku (in Japanese), Nikkei BP, pp.18-24 (2000).
- (6) JIS S-2302, Method of internal pressure test for carbonated beverage bottles (in Japanese), JIS Handbook, (33) Glass, JAS (2001).
- (7) Elembaas : The high pressure discharge, pp. 187-210, Philips press (1974).