Article Identifier
DOI: 10.22032/dbt.58682
URN: urn:nbn:de:gbv:ilm1-2023isc-005:5

60th ILMENAU SCIENTIFIC COLLOQUIUM
Technische Universität Ilmenau, 4 – 8 September 2023
URN: urn:nbn:de:gbv:ilm1-2023isc:1

BASIC CONSIDERATIONS FOR CIRCUMFERENTIAL ADHESIVE BONDS IN ORDER TO REDUCE LENS DEFORMATIONS

Torsten Erbe

ASML BV, 5504 DR Veldhoven, The Netherlands

ABSTRACT

A critical aspect of designing lens mounts is to minimize lens deformation, since shape and position of the optical elements determine the performance of an optical system. The mounting of the lens to the lens-cell is a major contributor to lens deformation and therefore of particular interest during the design – of the lens-mount as well as the lens itself.

A common technology used for lens mounting is the circumferential adhesive bonding. The adhesive system of lens-cell, lens, selected adhesive has been discussed in the literature predominantly focussing in minimizing forces on the lens at different temperatures by defining a optimized glue gap. However, these models are not always applicable due to volume constraints, technological restrictions and/or the different dimensions of lenses.

Therefore this paper will focus on minimization of the effect of these forces by the design of the adhesive bond rather than reducing the amount of force itself. By applying straight robust design principles a rather simple way to minimize lens deformation for common lens mount concepts will be presented.

A model to calculate the forces of a circumferential bond towards a lens will be presented. It will be pointed out how the position and shape of the circumferential adhesive bond can be optimized in order to minimize lens deformation due to forces transferred via the glue.

Index Terms **–** Lens mount, robustness, design principles, lens aberrations, adhesive bonds, opto-mechanics

1. INTRODUCTION

Circumferential adhesive bonding of a lens to a lens-cell is often used since the gluing process can be automated and the connection can be made fluid-tight. During the design of optical systems, a major design goal is to minimize deformations of optical elements.

This holds for high end optical system (e.g. in semiconductor industry) with its distinct opto-mechanics as well as for more common optics (e.g. in cameras, scopes) [1-3]. The adhesive system of lens-cell, lens, selected adhesive and - if relevant - intermediate layers have been discussed in the literature and models (see Table 1) are proposed to calculate the optimal glue gap g_{opt} for a given set of material and adhesive [1,4-9].

However, these models are not always applicable in an optical system due to the different dimensions and materials of lenses given by the optical design itself as well as volume constraints or technological restrictions. Lenses inside an objective lens potentially consist of dissimilar materials but might have similar outer diameter which makes the application of the aforementioned models complicated if not impossible for all lenses.

Even if well applied, established models (summarized in Table 1) assume a thermal equilibrium inside the objective lens and neglect forces like shrinkage of glue e.g. during curing or by dry-out. Furthermore, external loads/forces transmitted to the lens via the adhesive bond are not regarded.

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***Table 1:** Common models to calculate the optimal adhesive gap for lenses*[1]

Equation	Comment
Bayar equation [1] $g_{\mathrm{opt}} = \frac{r_{\mathrm{L}} \cdot (\alpha_{\mathrm{C}} - \alpha_{\mathrm{L}})}{\alpha_{\mathrm{A}} - \alpha_{\mathrm{C}}}$ eq. 1	▪ linear approach assuming a non-constraint adhesive bond and infinite stiff lens-cell
Van Bezooijen equation [8][2] $g_{\mathrm{opt}} = \frac{r_{\mathrm{L}} \cdot (\alpha_{\mathrm{C}} - \alpha_{\mathrm{L}})}{\alpha_{\mathrm{A}} - \alpha_{\mathrm{C}} + \frac{2 \cdot \nu_{\mathrm{A}}}{1 - \nu_{\mathrm{A}}}\left(\alpha_{\mathrm{A}} - \frac{\alpha_{\mathrm{L}} + \alpha_{\mathrm{C}}}{2}\right)}$ eq. 2	▪ assumes an adhesive bond constrained by the lens and the lens mount with $h_b/g > 1$ ▪ lower limit of the glue gap of a circumferential adhesive bond assuming an infinite stiff lens-cell
modified Van Bezooijen equation [9] $g_{\mathrm{opt}} = \frac{r_{\mathrm{L}} \cdot (\alpha_{\mathrm{C}} - \alpha_{\mathrm{L}})}{\alpha_{\mathrm{A}} - \alpha_{\mathrm{C}} + \frac{\nu_{\mathrm{A}}}{1 - \nu_{\mathrm{A}}}\left(\alpha_{\mathrm{A}} - \frac{\alpha_{\mathrm{L}} + \alpha_{\mathrm{C}}}{2}\right)}$ eq. 3	▪ assumes an adhesive bond constrained by the lens and the lens mount with $h_q/g \approx 1$ ▪ upper limit of the glue gap of a circumferential adhesive bond assuming an infinite stiff lens-cell

This paper will focus on minimization of the effect of the forces caused by curing/shrinkage of glue as well of those transmitted via the glue by the design of the adhesive bond rather than minimizing forces themself. Therefore, the following research questions about the position and shape of the circumferential adhesive bond will be discussed in this contribution:

- *How can an optimum position of the adhesive bond be found with respect to the lens?*
- *How to design the circumferential bonding features of a lens-cell to minimize deformation of the glued lens?*

These research questions are discussed based on the simple circumferential adhesive bonded lenses (CABLs) only. However, transferable aspects of the results to more complex lens-cell designs (e.g. [10,11]) is pointed out.

2. TYPS OF CIRCUMFERENTIAL ADHESIVE LENS MOUNTS

Mounting concepts for optical elements can be classified in separate ways.
Table **2** shows a very general classification according to the direction of the forces and the type of coupling used for holding the lens in the lens-cell.

***Table 2:** Classification of lens mounting principles; class in scope in italic*

type of coupling / direction of force	force fit	form fit	material fit
across the optical volume	radial clamping [12-14]	“radial” kinematic mount [15][1]	*adhesive bonds, soldering* [20]
outside the optical volume	longitudinal clamping [10,16]	threaded ring [1,17], Kinematic mounting [18,19]	adhesive bonds, soldering, potting

Within this paper the scope is limited to the mounting of rotationally symmetric optical elements (i.e. lenses) with a circumferential adhesive bonded.
Several types of embodiment designs are known for this class (exemplarily in Table 3) which are (often without distinction) called CABL. In the following only radial circumferential bonding of a lens (see Table 3 a)) will be regarded.

[1] α_{L} … coefficient of thermal expansion (CTE) of the lens; α_{C} … CTE of the lens-cell; α_{A} CTE of the adhesive, r_{L}…radius of the lens at the bond line; υ_{A} … Poisson number of the concerned adhesive; g … thickness of the bondline (radial); h_{B} … height of the bond line (perpendicular to g)
[2] The reference [8] was not accessible directly but was cited in [9] and is therefore taken over from [9].

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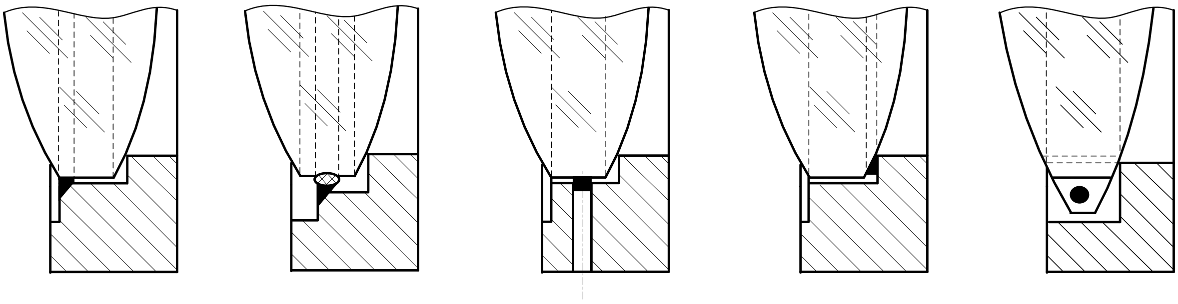
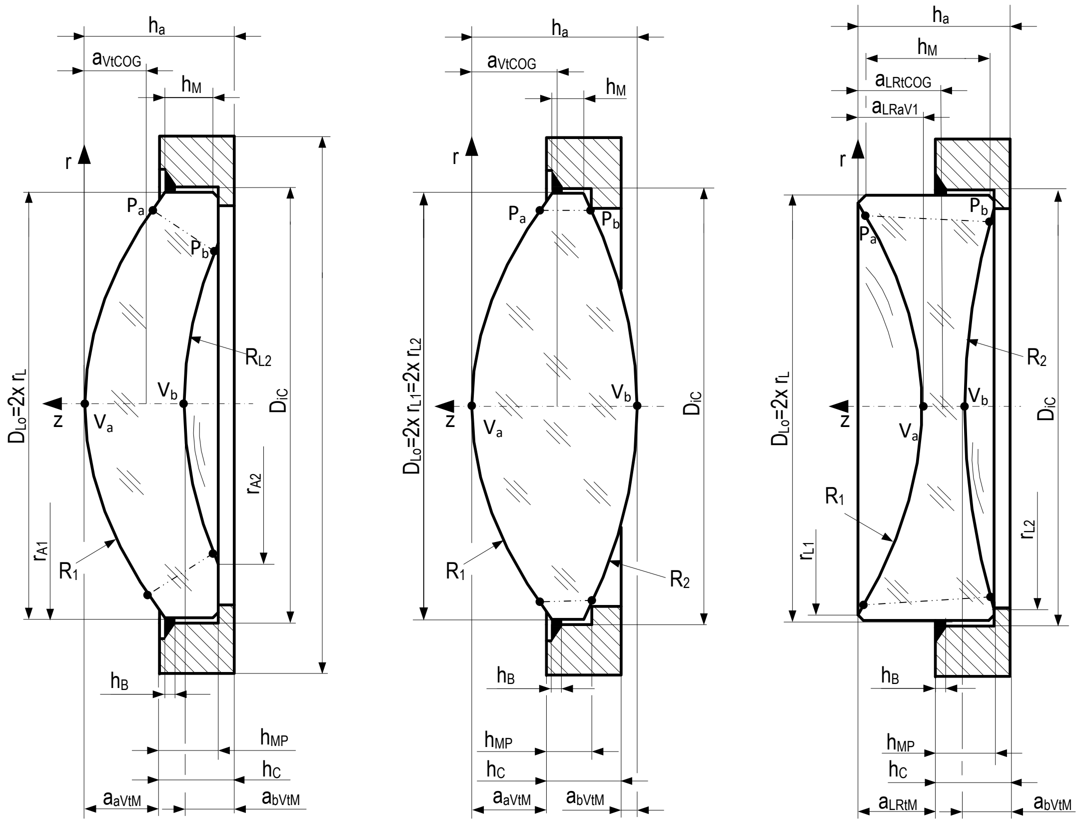
Table 3: *Overview of common circumferential adhesive mounting concepts; exemplified for a biconvex lens*[3]



a)	b)	c)	d)	e)
radial circumferential adhesive mounting	radial circumferential adhesive mounting with an intermediate elastic ring	*N* circumferential distributed adhesive dots/intermitted segments at the lens ($N \geq 3$)	„axial" circumferential adhesive bond	*N* tangential distributed adhesive dots at lens protrusions ($N \geq 3 \times i$)

This common CABL design allows to automate the gluing process and the bondline can easily be inspected [3,21]. In this type of CABL design, the lens is resting on either:

- a circular cutting edge with its spherical surfaces (defining the all lateral DOF) or
- a cutting edge/flat surface with a flat side (defining one lateral and two rotational DOF) (see Figure 1).



a) *b)* *c)*

- ***Figure 1:*** *Section view of circumferential adhesive bonded lens mounts showing the adhesive bond (black wedge) and circular knife-edge for a) a convex/concave (meniscus)-lens, b) a biconvex and c) a biconcave lens.*

[3] With *N* as the number of glue dots needed (minimal for *i*=1).

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In both cases the lens is held in position with respect to the lens-cell by a circumferential adhesive bond. External forces – i.e. due to curing or mechanical and thermal loads – on the optical-element are transferred from the lens-cell to the lens via the adhesive bond and the circular knife-edge[4] contact.

Radial forces applied via the bondline will compress/stretch the lens and might cause "bending" of the lens.

The straightforward approach is, to minimize forces caused e.g. by temperature changes or shrinkage by a suitable choice (by applying the aforementioned approaches) of the glue gap g_{opt} in combination with lens mount materials and adhesive as well as minimizing the bondline – the area where the adhesive is holding the lens - itself. Why this approach is not (always) possible is discussed in the following sections.

2.1 Dimensioning of the adhesive bond at a glance

The main task of the adhesive bond is to create a stable connection between lens and lens mount. Due to variations safety factors are applied and the adhesive bond area in contact with the lens is often larger than needed for the application itself (see Figure 2).

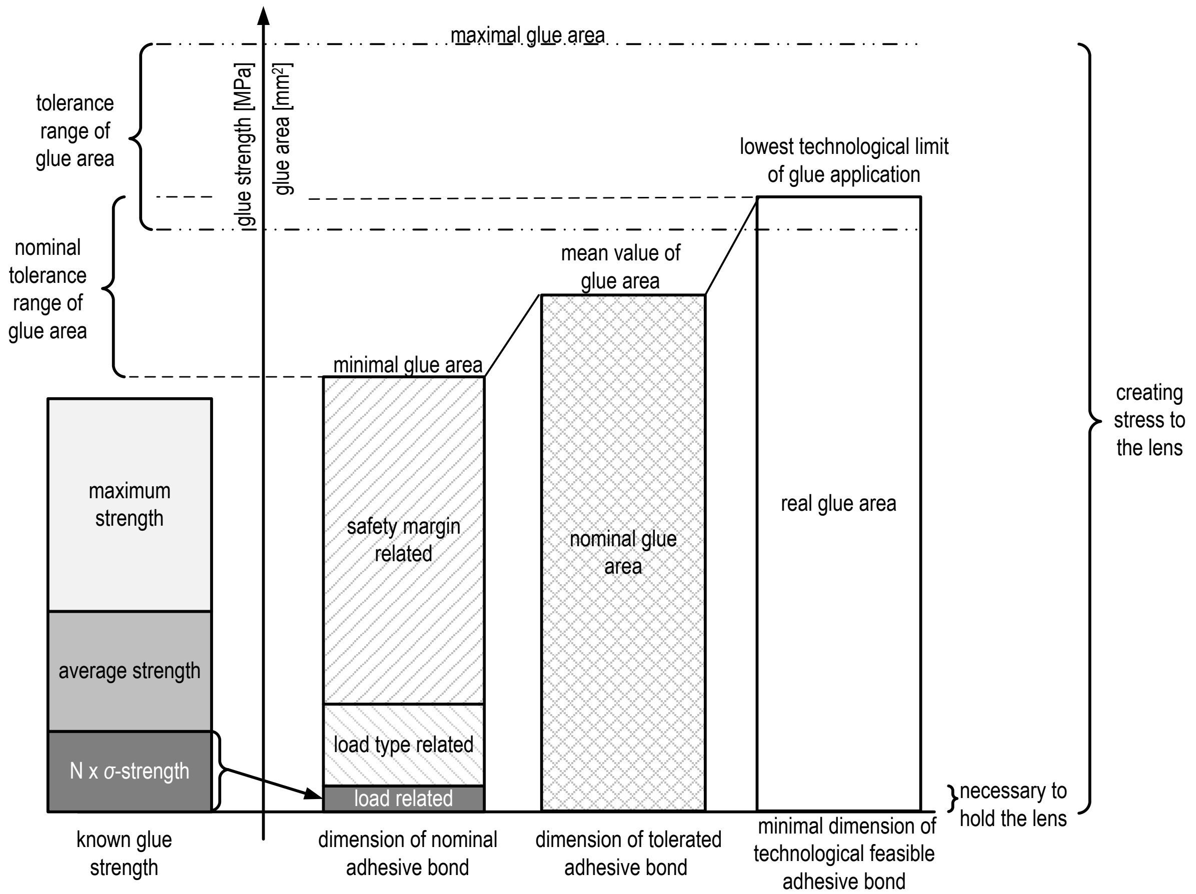

***Figure 2**: Overview of reasoning which determines adhesive bond area for small and medium lenses. Note: application tolerances can be asymmetric.*

[4] The circular cutting edge is a precision feature with a radius of ≈0.01 mm and an internal run out of ≈0.001 mm realizing a line contact between the lens and the lens-cell. The design of the circular cutting edge is discussed in literature [21-23] but is likely different for each manufacturer due to experience/technology used.

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The main reasons for excessively large bond lines are:

1. Loads during operation might be below those during other life phases (shock/vibration during transport, storage and transport, curing temperatures). Load cases not related to the application itself might therefore determine the design of the adhesive bond[5].

2. To deal with the lack of knowledge of damage mechanisms, load cases and scatter of properties of technical products, safety factors S_i are applied. Depending on experience and application these could include long-term effects (S_T e.g. crack-propagation), stress-type (S_B; e.g. bending, tension), load frequency (S_L; e.g. shock, vibrations), load-duration (S_D; e.g. rarely or often), bond-realisation in production environment (S_R; e.g. reproducibility of glue dot size) as well as more generic "global-safety-factors" (S_G; e.g. unknown load/quality fluctuations).

3. Since adhesive parameters differ and have a decent variation depending on the adhesive system, strength values with a reasonable confidence level (e.g. 3σ) and below the nominal strength are used for dimensioning of the bond area.

4. The adhesive bond area needs to cover a reasonable dimension in height of the lens mantle surface to ensure a reproducible bond. What is to be assumed "reasonable" depends e.g. on the wetting behaviour of materials/adhesive and the technology used for application.

Therefore, bondlines are often larger than "functionally" (during application) needed. This can be exemplified for a d_L=76 mm diameter lens with a weight of m_L=50 g which is objected to G=30 G[6] shock load and bonded with *2216 B/A*[7] (σ_A=22 MPa).

The nominal height h_{min} of the circumferential adhesive bond needed, with all safety factors assumed to be S_x=2 is just 0.2 mm (see eq. 4).

$$A_{aL} = h_B \cdot \pi \cdot d_L \geq \frac{S_T \cdot S_B \cdot S_L \cdot S_D \cdot S_R \cdot S_G \cdot m_L \cdot G}{\sigma_A \cdot d_L \cdot \pi} \cdot h_{min} \qquad \text{eq. 4}$$

Even by using these safety margins and by assuming an automated bonding process, reproducing a constant bond line of 0.2 mm height is a demanding task. As a rule of thumb, a circumferential bond line height h_B of less than 1 mm will require specific measures for the gluing process and subsequently quality control to ensure reproducibility of the bonding process by i.e. bondline height and fluctuation of contacting area. Therefore, further on in this work a bond line height h_B of 1 mm is assumed as a baseline.

Note, for the chosen example, the size of the bond line will lead to a five times larger bond area than needed - even after applying safety factors. Altogether this will result to sixty times(!) larger bondline than nominally needed and consequently larger deformation due to e.g. shrinkage.[8]

2.2 Adhesives for circumferential adhesive bonded lenses

Besides providing the forces needed to hold the lens, there are further requirements for the adhesive bond which might influence the choice of adhesive, like sealing, specific Eigenfrequencies and damping properties inside the objective lens or resistance to specific agents/fluids in application environment, etc. Furthermore, material compatibility, economic and technological restrictions need to be considered as well. Therefore, the adhesive choice is always a trade-off during CABL design.

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[5] Note: Elastic deformations and displacements during these non-use life phases can exceed the allowed functional limits if they are "recovering"/no subject to hysteresis.

[6] "30 G" means 30 times gravitational acceleration of 9.81 m/s^2

[7] See table Table 4.

[8] This level of over-dimensioning is one of the main reasons for "non-circumferential" bondlines.

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Table 4: Overview of adhesives for opto-mechanical bonds. The listed properties are indicative only and depend on load case, design (e.g. material, geometry of the bond), process (cleaning, curing, pre-stressing), load parameters and will be different below and above the glass transition temperature.

Adhesives	301-2	EA 9313 A/B	DP 460EG	9323 B/A	EK-93	2216 B/A	DP490	NOA 61
Prominent properties	very low viscosity	low viscosity	medium viscosity	high viscosity	very high viscosity	low glass temperature	high water resistance	one component. UV cured
Youngs modulus[2,3] [GPa]	2.3	2.2	2.36	2.3	0.16	0.07	0.66	0.15
Thermal conductivity[2] [W/(mK)]	0.24	-	0.26	0.25	1.25	0.39	-	-
CTE[2,3] @0-40 °C [ppm/K]	39	-	90	90	62	102	100	240
Lap shear strength [MPa][2,3,5] @23 °C	13.8	28	27	20	14-5	22	26	20
Shear modulus [GPa] @25 °C	0.85	0.88	0.86	0.82	-	0.342	0.24	-
Poisson Ratio[1,2]	0.36	0.36	0.37	0.4	-	0.47	0.4	-
Volume shrinkage[3] [Vol%]	1.5	6	2	4	0.1	2	2	4.0
Glass temperature[3] [°C]	65	40	50	60	100	23	50	-
TML[1,3] [%]	1.0	0.9	4.2	0-9	1.0	0.8	1.96	3.9
CVCM[1,3] [%]	0.01	0.03	0.06	0	0.03	0.04	0.01	0.03
WVR[1,3] [%]	0.4	0.2	0.9	0-4	-	0-2	0.5	0.2
RML[1,3] [%]	0.6	0.7	3.3	0-5	-	0-5	1.43	3.6
Viscosity mixed[2] [Pa s]	0.2	0.6-1.5	20	15-160	1000	40-150	500	0.30
Handling process/pot lifetime[2] [min]	60	60	60	120	30	90	90	n. a.
Time to handling strength [h]	6	8	4	5	1	12	6	n. a.
Curing time[4]	24h @23 °C or 2 h @65 °C	5 d @>25 °C or 1 h @82 °C	24 h @23 °C or 5 h @50 °C	15 d @23 °C or 2 h @65 °C	7 d @25 °C or 3 h @71 °C	7 d @24 °C or 2 h @66 °C	7 d @23 °C or 24 h @23 °C	UV cured; thermal post curing possible
Data source	[26]	[27]	[28]	[29]	[30]	[31]	[32]	[33]

[1] *... acc. [34,35] and technical datasheets of individual adhesives*
[2] *... @ 25°C*
[3] *... depends on heat treatment during production, i.e. curing*
[4] *... much more curing cycles are possible, the noted ones are regarded exemplarily*
[5] *...depends among others on the adhesive system and the fabrication process, i.e. material and surface quality/preparation*

There is a range of structural adhesives known for opto-mechanical applications. Table 4 lists a selection of properties of some of them without claiming completeness.

3. LENS DEFORMATION

Demands on the quality of optical surfaces are high and allowed deviations of the nominal geometry are in the order of only a few nanometres [36]. Although summed-up statistically, acceptable form deviations due to the mounting technology are usually in order nanometres. Potential causes for lens deformations are:

- different expansion coefficients of materials used, uneven heat-loads during application and heat-capacities of lens, adhesive and frame [4,6],
- different/changing orientation of the lens in the gravitational field i.e. with respect to the orientation during assembly [24],
- external forces to the lens (e.g. shock during transport) [25] and/or

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- tensions in the lens due to deformation of the sockets after gluing caused by the assembly of add-on parts during fabrication and usage of a lens.

The resulting forces to the objective lens are transmitted via the adhesive bond to the individual lens, causing its deformation and so affecting the performance of the entire optical system. With respect to the design of the adhesive bond itself, the main contributors to lens deformation are:

- forces due to shrinkage caused by curing, dry-out, thermal expansion of elements of the adhesive system,
- forces/torques to the lens due to deformation of the lens-cell caused by (the assembling of) other parts and
- changes of forces between lens and lens-cell at the knife edge contact (during all life cycles).

However, lens form deviations before system assembly could (to some extend) be compensated or corrected by systems adjustment means and measures – deviations happening afterwards cannot. Therefore, in the following, the scope will be to make the design insensitive to these forces and – as a result – to changes of them without focussing of the root cause of the change itself. Or to put it differently, the presented approach is not aiming to minimize the force itself, but the sensitivity of the lens-mount to it.

3.1 Model for lens deformation

For all CABL in scope the circumferential adhesive bondline is applied to the mantle of the lens, whereby the available mantle area can be calculated acc. to eq. 5 to eq. 11.

$$h_{\mathrm{Ml}} \geq h_{\mathrm{Mh}} \qquad \text{eq. 5}$$

$$h_{\mathrm{Mh,min}} = \pm R_{\mathrm{L1}} \pm \frac{1}{2}\sqrt{4R_{L1}^2 - r_{\mathrm{A1}}^2} + h_{\mathrm{F}} + \frac{h_{\mathrm{B}}}{2} \qquad \text{eq. 6}$$

$$h_{\mathrm{Ml,max}} = \pm R_{\mathrm{L2}} \pm \frac{1}{2}\sqrt{4R_{\mathrm{L2}}^2 - r_{\mathrm{A2}}^2} - h_{\mathrm{F}} + h_{\mathrm{La}} - \frac{h_{\mathrm{B}}}{2} \qquad \text{eq. 7}$$

$$\pm R_{\mathrm{L2}} \mp R_{\mathrm{L1}} \mp \frac{1}{2}\left(\sqrt{4R_{\mathrm{L2}}^2 - r_{\mathrm{A2}}^2} + \sqrt{4R_{\mathrm{L1}}^2 - r_{\mathrm{A1}}^2}\right) - 2 \cdot h_{\mathrm{F}} + h_{\mathrm{La}} - h_{\mathrm{B}} \geq 0 \qquad \text{eq. 8}$$

The height of the mantle area must be at least as large as the bondline h_{B} contacted to the lens after taking chamfers h_{F}[9] and cut-offs h_{La} into account. By subtracting those, the edge of the usable height of the mantle area can be defined with respect to one vertex by $h_{\mathrm{Ml,max}}$ and $h_{\mathrm{Mh,min}}$. If the height of the mantle area $h_{\mathrm{Ml,max}} - h_{\mathrm{Mh,min}}$ is larger than h_{B} the position of the bondline at the mantle can be optimized to minimize the lens deformation.

For modelling of CABL, the adhesive bond and thus the loads to the lens are assumed to be radially symmetric. The difference between the order of magnitude of the here discussed deviations and the dimensions of the parts involved, allows further simplifications to the models like:

- simplification to a 2D-problem with four characteristic points (see Figure 3),
- only elastic deformations are assumed (see Figure 4) and/or
- Youngs modulus is assumed to be constant (not strain, temperature, curing, etc. depended).

Furthermore, since the Youngs-modulus of glue is typically about 100x smaller than those of lens and lens-cell both are assumed as stiff. The proposed models will therefore focus on the forces applied rather than the deformation of the lens itself.

[9] Almost all lenses will have protective chamfers typically ranging from 0.1 to 0.3. These are not shown in Fig. 3 but supposed to be regarded in the calculation as well.

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The models are regarding lens deformations caused by:

- forces at the vertices of the lens V_a and V_b due to radial forces at the adhesive bondline,
- displacement of the lens with respect to the lens-cell in z-direction due to constraint shrinkage of the glue at the adhesive bond.

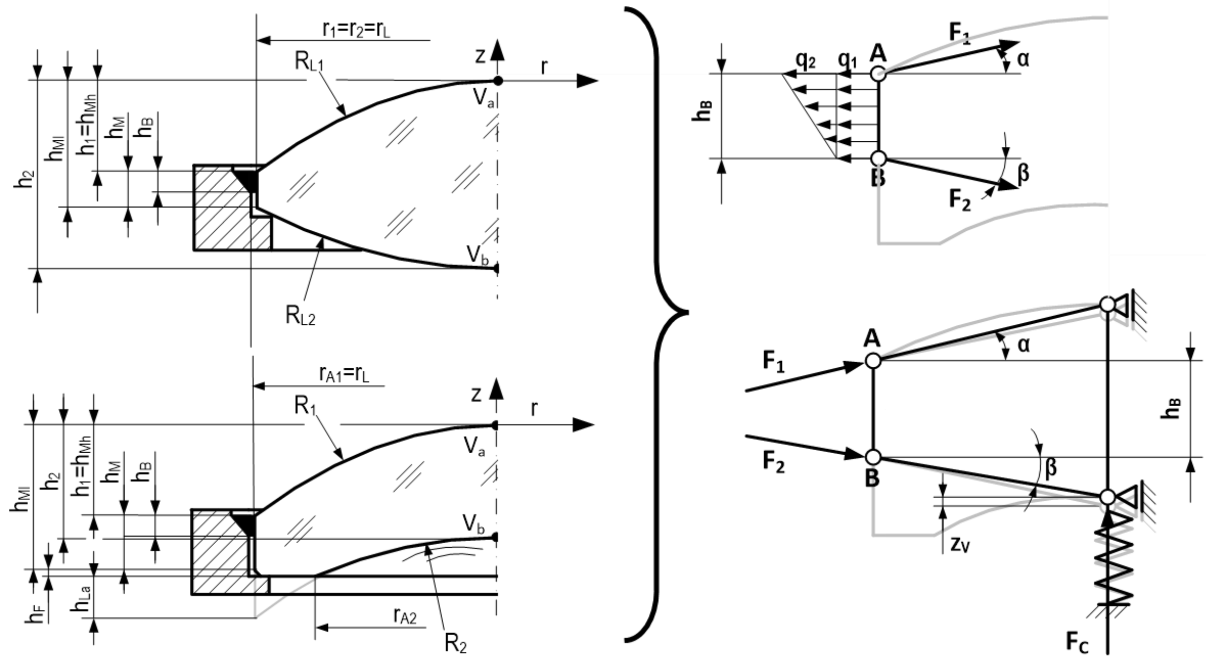

***Figure 3**: Basic lens model, assuming a rotationally symmetric load. Left side shows the lens geometry, the right side shows the model approach.*

Note, that the amount of force is not regarded in these models since the aim is to minimize the effect of the force applied to the lens as much as possible.

3.2 Case 1: Optimization of adhesive bond location at the lens mantle

In the first case a symmetric bond with a radial load q=f(z) applied by the adhesive (e.g. due to shrinkage or thermal effects) is assumed. The contact at the knife edge of the lens-cell as well as the potential compression of the lens (→ $F_{zVa}=F_{zVb}=F_{zV}$) is neglected.

A change of curvature of the lens is caused by a force to the vertices in z-direction. The change of curvature is therefore reduced by minimization of F_{zV} according to the following eq. 9 and eq. 10.

$$|F_{zV}| = |c \cdot \Delta z_v| = |F_1 \cdot \sin\alpha + F_2 \cdot \sin\beta| \quad \text{eq. 9}$$

$$|F_c| \rightarrow \text{min}; |\Delta z_v| \rightarrow \text{min} \quad \text{eq. 10}$$

The forces F_1 and F_2 can be derived from the load applied by the adhesive bond and split into a radial and axial contribution (see eq. 11 to eq. 14).

$$\sum_1^k F_{kZ} = 0 = F_1 \cdot \sin\alpha - F_2 \cdot \sin\beta \quad \text{eq. 11}$$

$$\sum_1^l F_{lR} = 0 = q_1 \cdot h_B + q_2 \cdot \frac{h_B}{2} - F_1 \cdot \cos\alpha - F_2 \cdot \cos\beta \quad \text{eq. 12}$$

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$$\sum_{1}^{m} M_{m\mathrm{A}} = 0 = -F_2 \cdot \cos\beta \cdot h_\mathrm{B} + q_1 \cdot \frac{h_B^2}{2} - q_2 \cdot \frac{h_\mathrm{B}^2}{6} \qquad \text{eq. 13}$$

$$\sum_{1}^{n} M_{n\mathrm{B}} = 0 = F_1 \cdot \cos\alpha \cdot h_\mathrm{B} - q_1 \cdot \frac{h_\mathrm{B}^2}{2} - q_2 \cdot \frac{h_\mathrm{B}^2}{3} \qquad \text{eq. 14}$$

The minimization task (acc. eq. 10) can therewith be described as a function only depending on loads and geometry eq. 15 which could be separated by expanding to eq. 18:

$$\left|\left(\frac{1}{2}q_1 + \frac{1}{3}q_2\right) \cdot h_\mathrm{B} \cdot \tan\alpha + \left(\frac{1}{2}q_1 + \frac{1}{6}q_2\right) \cdot h_\mathrm{B} \cdot \tan\beta\right| \rightarrow \min \qquad \text{eq. 15}$$

$$\tan\alpha = \frac{h_1}{r_\mathrm{L}};\ \tan\beta = \frac{h_2 - h_\mathrm{B} - h_1}{r_\mathrm{L}}; \qquad \text{eq. 16}$$

$$\left|\left(\frac{1}{2}q_1 + \frac{1}{3}q_2\right) \cdot h_\mathrm{B} \cdot \frac{h_1}{r_\mathrm{L}} - \left(\frac{1}{2}q_1 + \frac{1}{6}q_2\right) \cdot h_\mathrm{B} \cdot \frac{h_2 - h_\mathrm{B} - h_1}{r_\mathrm{L}}\right| \rightarrow \min \qquad \text{eq. 17}$$

$$\frac{\left(\frac{1}{2}q_1 + \frac{1}{3}q_2\right)}{\left(\frac{1}{2}q_1 + \frac{1}{6}q_2\right)} = \frac{h_2 - h_1 - h_\mathrm{B}}{h_1} \qquad \text{eq. 18}$$

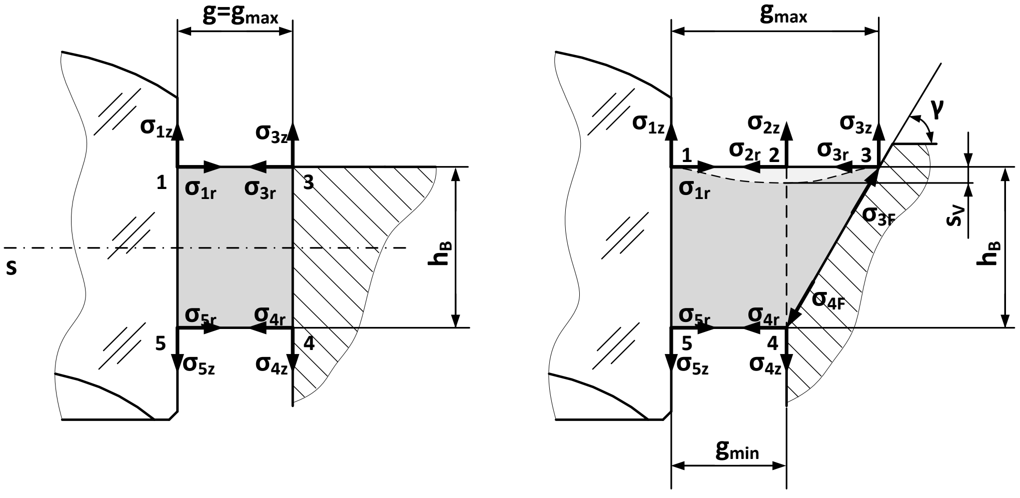
By using eq. 18 the bending moment of the lens can be minimized by defining h_1 and h_B. However, it also becomes clear, that a small bondline (h_B) increases the range of optimization. Since it helps to fulfil the following condition eq. 19.

$$h_2 \geq 2 \cdot h_1 + h_\mathrm{B} \leq h_\mathrm{Ml} - h_\mathrm{Mh} \qquad \text{eq. 19}$$

A first conclusion is that for q_2=0 the height $h_1 = \frac{h_2 - h_\mathrm{B}}{2}$ becomes a function invariant to radial forces caused by or transmitted through the glue. In order to achieve this desirable state the effects causing q_2 need to be minimized as well. For the radial forces concerned, q_2 stands for the stiffness of the bond which depends on Youngs-modulus and shape of the (since 2D and symmetrical: cross sections of) bondline[10]. The latter is regarded in the next chapter.

3.3 Case 2: Lens displacement due to adhesive bond embodiment shape

Due to technology limitations and for accessibility – to put in the lens itself or in order to apply the glue – the adhesive is often filled in a circumferential bevel with a bondline angle γ (this appears to be a trapezoid or triangle in section view, see Figure 4).



[10] Note: This depends on other factors like e.g. the load case or whether the optic is cooling down or heating up as well.

Figure 4: *Basic bondline section view, assuming a (simple bevel) for glue application.*

The condition q_2=0 is valid if eq. 20 and eq. 21 are fulfilled. This is e.g. the case for glue shrinkage if Youngs-modulus is isotropic and if lateral strain ε_A is neglected (see eq. 22 to eq. 24). But even with these assumptions it does not hold true for e.g. thermal effects, where the strain is a function of the glue gap g_i and the CTE of the materials involved. In this case eq. 21 is only fulfilled for bond lines symmetric to *s*.

$$\begin{aligned}\sigma_{1r} + \sigma_{3r} &= 0 \\ \sigma_{5r} + \sigma_{4r} &= 0\end{aligned} \qquad \text{eq. 20}$$

$$\sigma_{1r} = \sigma_{5r} \qquad \text{eq. 21}$$

$$\varepsilon = \frac{\Delta l}{l} = \frac{\sigma}{E} = \frac{F}{A_{aL} \cdot E} \qquad \text{eq. 22}$$

$$\sigma_{1r} = E \cdot \varepsilon_A \qquad \text{eq. 23}$$

$$\sigma_{5r} = E \cdot \varepsilon_A \qquad \text{eq. 24}$$

In the limitations/assumptions of the proposed model the symmetry of the bondline is in general favourable since it also cancels out lateral strain effects. The latter could – due to constraint shrinkage – cause a force in *z*-direction to be applied to the lens. This force is a function of the Youngs-modulus of the glue E_A, the bondline height h_B and the shift s_V caused by lateral strain $\left(\frac{\upsilon \cdot \varepsilon_A}{2}\right)$ (see eq. 25 to eq. 32).

$$\begin{aligned}\sigma_{1z} + \sigma_{5z} &= 0 \\ \sigma_{2z} + \sigma_{4z} &= 0\end{aligned} \qquad \text{eq. 25}$$

$$\frac{\sigma_{1z}}{E} = \frac{\varepsilon_A}{2} - \frac{s_V}{h_B} \qquad \text{eq. 26}$$

$$\frac{\sigma_{5z}}{E} = -\frac{\varepsilon_A}{2} + \frac{s_V}{h_B} \qquad \text{eq. 27}$$

$$\frac{\sigma_{2z}}{E_A} = \left[\frac{\varepsilon_A}{2} - \upsilon \cdot \frac{\varepsilon_A \cdot (g_{max} - g_{min})}{g_{max}} + \frac{s_V}{h_B}\right] \qquad \text{eq. 28}$$

$$\frac{\sigma_{4z}}{E_A} = -\frac{\varepsilon_A}{2} + \frac{s_V}{h_B} \qquad \text{eq. 29}$$

$$\upsilon \cdot \frac{\varepsilon_A \cdot (g_{max} - g_{min})}{g_{max}} + 2 \cdot \frac{s_V}{h_B} = 0 \qquad \text{eq. 30}$$

$$g_{min} = g_{max} \cdot \sin\gamma \qquad \text{eq. 31}$$

$$\frac{\upsilon \cdot \varepsilon_A}{2} \cdot (\sin\gamma - 1) \cdot h_B = s_V \qquad \text{eq. 32}$$

$$F_{ZL} = \frac{s_v}{h_B} \cdot E_A \cdot A_{aL} = \frac{\upsilon \cdot \varepsilon_A}{2} \cdot (\sin\gamma - 1) \cdot E_A \cdot \pi \cdot d_L \cdot h_B \qquad \text{eq. 33}$$

Assuming that $g_{max} \neq g_{min}$ a force F_{ZL} can be calculated acc. to eq. 33 which is – for the example chosen in Figure 4 - pushing the lens onto the knife edge of the lens cell. However it need to be noted, that – since the presented approach is neglecting the non-linearity of e.g. Youngs-modulus and root causes of the strain – a calculation just applying values e.g. from Table 4 will result in highly exaggerated forces[11]. For a fair estimate of the force itself a non-linear calculation e.g. by using transient FE-models with non-linear material models is needed.

[11] For the lens described in chapter 2.1, with a bondline angle γ=45° this would result in >894 kN of force. This is arguably too high to be sustained by a lens.

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4. DISCUSSION OF RESULTS GAINED BY PROPOSED MODELS

Although the proposed models are only regarding a deformation along the optical axis the influence – and therewith the potential for optimization - of geometry and position of the circumferential bondline becomes clear. Both models point out the relevance of symmetry for bond line geometry and location with respect to the lens. Even if this is not very surprising, the models can be used for:

- Regarding lens deformation during optical design, since an optimal location of the bond line can be found in all cases for bi-concave lenses (Figure 1c)) often for bi-convex lenses (Figure 1b)) and only for decent meniscus-lenses (Figure 1a))
- For geometrical tolerancing of lens cells since the criticality of geometric aspects can be calculated. Within the constraints mentioned in eq. 19 an optimal bondline position could be calculated with eq. 18.
- It becomes obvious that the forces which are pushing the lens onto the knife edge for γ=90° are zero. Therefore, an imprint of less precise (in order of micrometres) knife edge into the lens is minimized. An angle of γ>90° can even create a lift of the lens from the knife edge.

Regarding the adhesive bond geometry, it is worth noting that fluctuations of the bondline thickness itself are not relevant if there is no force pushing the lens onto the knife edge. These fluctuations will not lead to a larger deformation.

By the partial differential eq. 34 of eq. 33 with respect to the angle γ (the other partial differentials are constants) the sensitivity of the individual geometry parameters – and therewith of manufacturing tolerances- can be calculated. It becomes obvious that a bondline without a bevel (γ=90°) is less sensitive to manufacturing tolerances. This aspect – like the symmetry – will make the lens mount design more robust regarding manufacturing tolerances.

$$\frac{\partial F_{\mathrm{ZL}}}{\partial \gamma} = \frac{\upsilon \cdot \varepsilon_{\mathrm{A}}}{2} \cdot \cos\gamma \cdot E_{\mathrm{A}} \cdot \pi \cdot d_{\mathrm{L}} \cdot h_{\mathrm{B}} \qquad \text{eq. 34}$$

Even if the stiffness of the lens cell is not (as regarded in the models) infinite or even intentionally reduced by compliant features (e.g. [11], [12]) the position of the bond line is still relevant while the optimal bondline geometry depends on the compliance of the lens cell features. This also holds for non-circumferential bonding like those shown e.g. in Table 3c.

A further way – not discussed here – of "directing" the forces at the lens is to use non cylindrical outer lens contours e.g. like a shallow conical shape, which might be a way to create bondline angles of γ>90° as well.

While the baseline assumption used in the shown models is the presence of external forces induced to the lens via the circumferential bond, it is important to mention that the first approach should always be to minimize these forces. Since the bondline thickness g is not part of the models discussed in this paper, approaches like those shown in Table 3c and careful selection of glue are still meaningful to apply.

5. CONCLUSION

The potential to minimize lens deformation even with those rather simple approaches becomes obvious. Although the effect of the application of the presented models as done in practice cannot be shown here, the models can be used as a starting point for lens cell designs with a further refinement of the specific design using FE- Analysis methods.

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CONTACTS

Dr.-Ing. Torsten Erbe

email: torsten.erbe@asml.com
ORCID: https://orcid.org/0000-0002-3032-9283

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