Optical Contact of Polished Glass Surfaces

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It is shown that the specific work required to separate two surfaces in optical contact is fairly constant and that the forces between two surfaces are effective at a very small distance, on the order of 10^{-7} cm.

1. CONCEPT OF OPTICAL CONTACT

THE word "contact" is frequently used in physical and technical literature as a self-evident concept. However, the fact that it is usually accompanied by the adjective "electrical," "mechanical," or "optical" shows that the concept "contact" requires a definition.

The term optical contact signifies the following phenomenon: two well-ground and polished plane glass surfaces adhere so strongly when placed on top of each other, that it becomes difficult to separate them. If the two glass surfaces have the same index of refraction, the optical contact reflects almost no light (the reflection coefficient from the hypotenuse faces of two total–internal–reflection prisms made of BK–10 glass, placed in optical contact, was measured by us to be roughly from 1×10^{-4} to 1×10^{-7}).

To separate two glass surfaces placed in optical contact, they are slightly heated (with a match or with a burner). The resultant elastic stresses create forces that are sufficient to break the contact. If the break has not been completed, both surfaces again make contact after cooling.

If the contact is placed in a liquid (water, alcohol or ethyl ether), the liquid penetrates into the contact zone and the contact-making surfaces may separate after a few hours. However, if the contact is removed from the liquid before separation, the liquid will evaporate gradually and the surfaces will adhere again. Such an experiment can be repeated several times with a single pair of surfaces placed in contact.

Surfaces in optical contact can be separated only by application of normal forces; they cannot be slid apart. Before the contact is completed, while a layer of air remains between the surfaces, they slide readily on each other. A pronounced symptom of the contact is that the surfaces stop sliding on each other, and attempts to slide them apart result at best case in only stripping (and usually scratching when two glass surfaces are placed in contact.

The condition of the surface plays a certain role in the establishment of an optical contact.

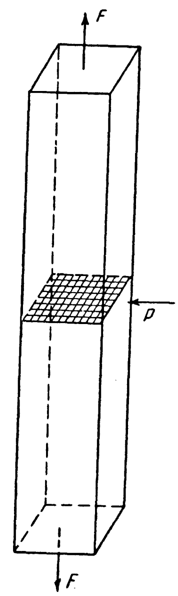

FIG. 1. Glass bars, placed in optical contact. FF—tension force, P—surface of optical contact.

Glass surfaces freshly polished with tar and rouge are very easy to place in contact, requiring only primitive surface cleaning—rubbing with alcohol and a clean rag and brushing the dust off. It is equally easy to establish contact between two silvered (wet method) glass surfaces. Thin laminae of anthracene, phenantrene and naphthalene crystals also produce an optical contact with glass, so strong that they must be scraped off or dissolved before they can be removed. Fire-polished glass surfaces, if they remain in air, are readily placed in contact, and if they are thin, they adhere so tightly, that they cannot be removed by neither scraping nor immersion in liquid. Surfaces cleaned by corona discharge lose their contact–making ability but regain it if the surfaces are left in the air for a while.

In spite of the fact that optical contact is a phenomenon well known to a large circle of physicists and technicians, it has been little investigated up to recently (disregarding many optical–engineering investigations devoted primarily to special technological problems). Optical contact is attributed to three causes: (1) pressure of the atmospheric air, (2) capillary pressure (adhesion) due to small traces of oil remaining on the surface of the glass, and (3) direct molecular attraction with the aid of molecular forces. Atmospheric pressure must be discarded: experiments on the separation of two glass bars placed in contact (Figure 1) have shown that the separation force always exceeds the atmospheric pressure, sometimes by a factor of several (up to seven) times. The choice lies between adhesion and the Van–der–Waals forces.

2. OBJECTS OF INVESTIGATION

To test optical contacts for strength, special specimens were prepared of a glass of nearly the same composition as K–8 glass (Figure 2). Each

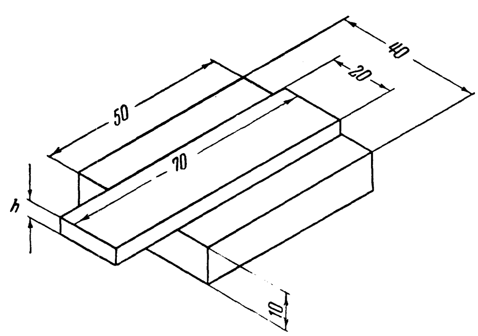

FIG. 2. Sketch of glass plates, placed in optical contact; $h = 0.5$, 1.0, and 2.0 mm. All dimensions are given in millimeters.

specimen comprises one thick and one thin plate. The thick plate was rectangular, measuring 50×40 mm with a thickness of 10 mm. Both wide faces and the two longer side faces of the thick plate were thoroughly polished for optical contact.

The thin plates came in three thicknesses: $h = 0.5$, 1.0, and 2.0 mm; all were 20 mm wide. The thin plate was placed in contact on the wide surface of the thick one. The thin plate projected 20 mm beyond the edge of the thick plate, polished with tar and rouge until bright, and the plates were placed in optical contact immediately after polishing was completed.*

The only cleaning done before establishing contact was to rub the contact–making surfaces first with a pad soaked in ethyl alcohol and then with a dry clean cloth napkin. This manner of establishing optical contact between our surfaces did not differ from the conventional manufacturing procedure.

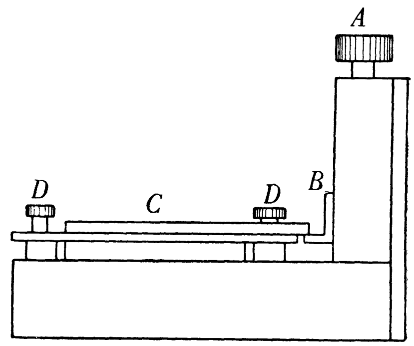

FIG. 3. Diagram of fixture for separating the optical contact. A–knob of lifting screw, B–hook used to separate the glass plate, C–glass plate, D–clamping screws.

3. METHOD OF OBSERVATION AND MEASUREMENT

The separation of an optical contact is usually difficult to observe because of the fact that the separation is very rapid and cannot be stopped at any intermediate phase. It is possible, however, to eliminate this shortcoming in the following manner: the specimen described in the preceding section is clamped in a special fixture (Figure 3) with the thin plate on top. A metal hook engages the projecting plate and is attached to the nut of a lead screw. The latter permits fine adjustment of the vertical motion of the tooth. When the nut moves up, the hook engages the projecting end of the upper plate and pulls it upwards. The resultant bending moment strips a portion of the upper plate. If the rise of the hook is stopped, the curvature of the plate and consequently also the stripping moment will diminish toward the contact zone until equilibrium is established between the stripping moment and the forces that bring the contact surfaces together. By regulating the rise of the stripping hook it is possible to set the boundary of the contact region in any location.

An air wedge is formed between the separated surfaces. If the separation region is examined in monochromatic light one sees pronounced interference fringes of equal thickness. From the thickness of these fringes it is possible to judge the shape of the bent upper surface, which turns out to be , as called for by the theory of elasticity, strictly parabolic. This is proven by the fact that the dis-

* Close contact of optical surfaces is used extensively by optical workers in those cases when cementing deforms the glass part or does not yield a dependable bond. In that case the part ground with carborundum is not polished to full brightness.

tance between the first and fourth interference fringes equals the distance between the fourth and ninth fringes and between the ninth and sixteenth fringes. Thus, it is possible to obtain the position of the zero fringe by extrapolation, i.e., to determine the place where the two plates come in contact. From the curvature of the upper plate one can also calculate the work required to strip the contact; in fact, the work required to strip the contact, calculated for one surface is

$$\alpha = K / 4\rho^2. \qquad (1)$$

here α is one quarter of the work required to strip one square centimeter of the contact surface, ρ the radius of curvature of the separated plate along the line of separation, and K is the stiffness, which for an isotropic rectangular plate is

$$K = Eh^3 / 12(1 - \sigma^2), \qquad (2)$$

where E is Young's modulus and σ is the Poisson coefficient.* Since the shape of the bent plate is parabolic, we have

$$y = x^2/2\rho, \qquad (3)$$

$$1/\rho = 2y/x^2 \text{ and } \alpha = Eh^3 y^2 / 12x^4 (1 - \sigma^2).$$

here x is the distance between the zero and the n'th interference fringe, y the thickness of the air layer, equal to $2n\lambda$, where λ is the wavelength of the light.

4. MEASURING THE WORK OF SEPARATION

As follows from Eqs. (1) and (2), to determine the work of separation of the optical contact it is necessary to know either the modulus of flexure of the glass plate, or the elastic constant of its material. Both were determined in this investigation. Since the glass plate bends along a parabola, the distances between the first and fourth, fourth and ninth, etc. interference fringes should all have an equal value, x_0 for normal incidence of the light and Eq. (1) becomes:

$$\alpha = Kn^2\lambda^2 / 4x_0^4. \qquad (4)$$

We used this equation to calculate α for the separation of the optical contact of all three thicknesses of plates. The results are given in Tables 1–3.

*It can be proven that when the contact is stripped half the work is consumed in bending the plate. The surface formed is 2 cm.^{2}

TABLE I

$h = 0.5$ mm, $\alpha_{av} = 36$ erg/cm^2

Number of experiment	α, erg/cm^2	Number of experiment	α, erg/cm^2
1	4.7	22	27.7
2	27.5	136	52.2
3	26.3	136	68.4
4	20.6	137	50.0
5	19.4	138	47.9
6	26.5	138	65.3
19	23.3	139	46.1
21	20.6	140	46.1

What attracts attention in these tables is not the large dispersion in the values of α, but the fact that in spite of the huge dispersion, one can still obtain average values for the work of separation of the optical contact.

The results of measurements on a plate 0.5 mm thick are given in Table I. The first column gives the number of the measurement; if several measurements bear the same number, this means that the experiment was performed in succession with the same specimen, but with a continuously lengthening separation region. The second column gives the values of α.

Table II gives the results for a plate made of the same glass but 1.0 mm thick. The results for the 2.0 mm plates are given in Table III.

5. REPRODUCIBILITY OF CONTACT

Anyone working with optical contacts knows that occasionally it takes time to establish contact between two glass surfaces. Thus, for example, in one of our experiments two plates, each 4 cm^2 in area and 5 mm thick, were first placed in contact, and separated by slight heating, upon which it became impossible to reestablish the contact. Two days later, however, without any action on the experimenter's part, the optical contact was restored spontaneously. Many such experiments lead us to believe that the possibility of a spontaneous repeated optical contact depends on its freshness. The fresher the contact, the less time elapsed since the first contact, the easier will it be restored, spontaneously, but this is not a law; the contact cannot be restored if the work of the primary separation is large.

It is easiest to restore a contact if the stripping was not carried out to the end and the two glass plates are not yet completely apart. In that case the contact moves back several millimeters when the stripping separating force is removed. The contact can always be restored by applying added pressure to the plates. Table IV illustrates one such experiment, which the specimen was kept in contact in a machine shop for 45 days. The following are the results of an experiment with repeated stripping of the contact (Table IV).

TABLE II

$h = 1.0$ mm, $\alpha_{av} = 28$ erg/cm^2

No. of experiment	α, erg/cm^2	No. of experiment	α, erg/cm^2	No. of experiment	α, erg/cm^2
23	39.7	51	19.5	63	67.2
25	30.6	52	21.2	64	22.4
26	21.6	53	14.2	65	24.9
27	47.7	54	31.2	65	29.0
28	32.5	55	33.1	66	29.0
31	26.1	57	31.1	67	31.3
32	24.4	58	48.7	68	31.2
43	21.4	59	35.3	69	29.0
45	13.6	60	23.4	131	36.6
46	8.4	60	29.0	132	35.8
47	11.9	61	22.4	134	21.2
48	12.1	62	24.9	135	43.8
49	3.7	62	29.6	135	55.7
50	21.4	63	22.4		

The first stripping (1) gives a rather high value of work of separation, usually not varying much from one section of the contact to another. The contact-making surfaces were not fully separated and after the stripping force was removed, the broken contact was spontaneously restored. Nevertheless, the contact boundary did not return to its initial position. After experiment (2) strong pressure was applied to the contact–making surfaces, a click was heard, and the contact was restored fully in its initial area. The work of separation then returned to its initial value.

TABLE III

$h = 2.0$ mm, $\alpha_{av} = 27.0$ erg/cm^2

No. of experiment	α, erg/cm^2	No. of experiment	α, erg/cm^2
36	7.3	87	36.2
37	8.5	88	36.2
38	8.3	89	38.3
39	7.1	90	38.3
40	6.9	91	37.0
41	5.8	100	10.2
81	43.6	101	29.6
82	41.1	102	36.3
83	41.7	103	69.2
84	45.0	105	9.2
85	37.3	106	9.0
86	40.6	107	8.7
86	44.2	108	8.3

Many experiments of the type reported in Table IV were performed; the full restoration of the contact by pressure is typical.

Table V gives the results of another series of experiments in which the contact was stripped and reestablished many times. The specimen was heated to 100° C in a muffle furnace prior to the experiment, but not again. The contact was restored spontaneously each time. The table lists the work of separation for the repeated strippings, and the constant value of this quantity is quite striking.

6. ELASTIC STRESSES IN THE REGION OF THE CONTACT

Viewing the specimens in contact through crossed Nicol prisms discloses slight brightening of the field, evidencing the presence of stresses. The bright regions are distributed unevenly over the surface of the contact.

When the specimen is viewed from the side a solid bright band is seen in the plane of the contact over the entire contact region. This gives an idea not only of the magnitude of the stresses but also of the large area of the stressed layer along the line of sight (Figure 4). Since the stressed layers on the two sides of the contact surface are not more than 0.1 mm thick, photographs magnified 5–12 diameters were taken with an MP–1 polarization microscope. The stressed regions which look solid when viewed with the naked eye, are actually broken up into individual sections and attenuate rapidly with depth. The region adjacent to the con-

TABLE IV

No. of experiment	Stripping conditions	α, erg/cm^2
1	a) First stripping	55.6
	b) First stripping (continued)	44.2
2	After spontaneous restoration of contact	21.4
3	Separation after restoration of contact under strong pressure	51.5

tact is therefore characterized by the presence of stresses perpendicular to the surface of the contact unevenly distributed in the plane of the contact, and attenuating rapidly with depth. The contact-making surfaces are thus subject in addition to adhesion forces also to elastic tension produced in the glass, when the contact is made. These stresses reduce the resistance of the contact to stripping and may be the cause of the fluctuations of α. These tensions in the glass become relieved after long time intervals (months), evidencing the plasticity of glass. This may be the cause of the increasing contact strength with time.

FIG. 4. Region of optical contact seen in crossed Nicol prisms. Magnification approximately 5 ×. *1–1*– contact line between two glass plates.

The stresses in the contact region are analogous to some extent to the stresses occurring near a surface crack in glass. Examination of a crack immediately after its formation shows that the stresses concentrate principally near the end of the crack and are perpendicular to its plane. After a relatively long time (several days), the stresses are no longer concentrated near the end of the crack.

Analogously, optical contact involves the appearance of local stresses in the immediate vicinity in the plane of contact. Upon stripping, the stresses completely disappear from the free surface of the plate, but the region adjacent to the contact line can be readily identified by the high stress concentration of stresses. A magnified micro-

TABLE V

Specimen No. 2, h=1.0mm

No. of stripping	α, erg/cm^2	No. of stripping	α, erg/cm^2
1*	141	10	29.7
2	25.6	15	20.3
7	21.6	25	26.0
9	22.9	50	20.3

*An accidental quantity. May be due to aging.

photograph of the contact line is given in Fig. 5, which is turned through 45° to save space.

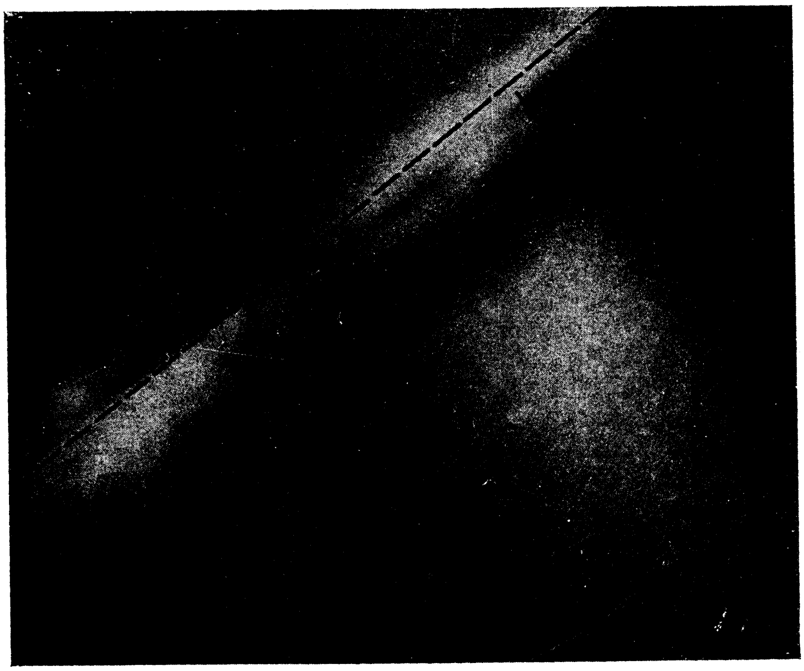

FIG. 5. Region of separation of contact as seen in crossed Nicol prisms. *1*—contact line; *2*—region of unbroken contact; *3*—contact boundary between two plates (thicker below, thinner above) with thickness of 0.5 mm; *4*—outer edge of thin plate; *5*—there is no more tension to the right of the arrow in the thick plate (below).

It is particularly interesting to view between crossed Nicol prisms the spontaneous restoration of contact upon reduction of the stripping force. One can see well under the microscope how the contact line moves over the specimen together with the stresses and how new local stresses appear again on the surface of the restored contact. These stresses are also indicative of the character of the adhesion forces in the optical contact. The stresses at the contact line are large and localized stresses, as shown in Fig. 5. They extend for 0.05 cm, and for this plate $2\rho = 4.5 \times 10^2$ cm. Consequently, assuming $y = 0$ at the start of the stressed region, we have at its boundary

$$y = \frac{x^2}{2\rho} = \left(\frac{2.5 \cdot 10^{-3}}{4.5 \cdot 10^2}\right) \text{ cm} = 5.6 \cdot 10^{-6} \text{ cm}.$$

This is the upper limit for y. The region of strongly-localized stresses may become indistinct if the axis of the polarization microscope is not directed along the contact line or else if the line itself is curved, as occurs frequently. Actually, the region of the localized stresses is sometimes much more pronounced. We once succeeded in observing stresses at the contact line in a region 0.1 mm in size, giving for y a value of 2.2×10^{-7} cm, i.e., on the order of the effective radius of the molecular forces. Thus, all data indicate that optical contact is sometimes accompanied by direct molecular forces between glass surfaces covered by adsorbed gas.

7. SINTERING OF OPTICAL CONTACT

It is known[5] that if surfaces in optical contact are carefully heated to a temperature even below the softening temperature of the glass, the two surfaces may sinter together, and can no longer be separated. A crack produced in the upper glass will pass through the lower one, and even if one succeeded somehow in separating the two sintered contact surfaces, they would be substantially damaged, parts of the lower surface stripping together with the upper one.

These results were confirmed in our experiments.

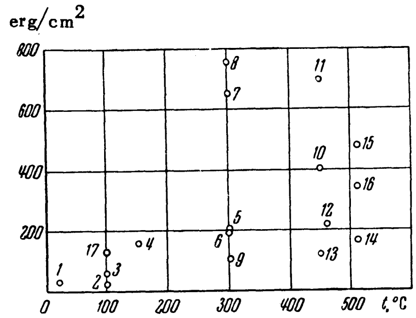

FIG. 6. Work of separation of optical contact as a function of the sintering temperature.

The specimens were heated in a muffle furnace. The temperature distribution in the furnace was first measured and the specimens were then located in the furnace in a region having a practically zero temperature gradient.

After many experiments we established a heating schedule resulting consistently in a fixed hot spot in the specimen. As a rule, this schedule left no temperature stresses in the heated specimen. Nothing happens to glass surfaces in optical contact heated to 100° C, the work of separation remaining almost unchanged. Upon carefully heating to 150° C and higher, occluded gas is liberated between the surfaces and separates them partially or totally (the contact is broken). Sometimes one plate floats above the other and unless they are perfectly horizontal, the upper plate may slide. When all the gas is liberated, the contact between the plates is spontaneously restored, with a sharp increase in the work of separation. Finally, at higher heating temperatures, the strength of the sintered contact increases to a value commensurate with the strength of the solid glass.

The behavior of one of the specimens is quite characteristic. Prior to heating, the average value of the work of separation fluctuated between 22.4 and 33.0 erg/cm.² A specimen with an incompletely restored contact region was heated in a muffle

TABLE VI

Temperature, °C	Work of separation after sintering erg/cm²	Thickness, mm	Remarks
20	30	—	Average of numbers obtained prior to sintering
100	17.4	1	
100	58.4	1	
150	156	1	
300	205	2	Region of multiple stripping
300	195	2	
300	650	2	
300	753	2	
450	113	1	Region of multiple stripping
450	400	1	
450	690	1	
460	216	0.5	Broke when stripped
300	100	2	Repeated sintering (after stripping
510	156	1	Region of multiple stripping
510	472	1	
510	339	1	
100	140	1	

furnace to 450 °±10° C and tested after slow cooling in the furnace to room temperature. The exterior surfaces, although retaining their optical properties, were changed. Where a wooden stick could previously glide easily over the glass, it now stuck tothe surface and scratched it. The measured work of separation were high, from 113 to 400 erg/cm² . The contact line became highly irregular and serrated. When the stripping moment was reduced to zero, the contact line did not return spontaneously to its previous location, and the contact was not restored. In the new separation region, when viewed in reflected light, one could see almost a uniform, gray, structureless field. The optical contact could not be restored by external pressure on the contact surfaces. A sharp boundary was formed between the old contact line(prior to sintering) and the new separation region; this boundary can be attributed to permanent flexure and bending of a previously flat surface.

The maximum reliably–measured value of the work of separation in a specimen heated to 450° was 400 erg/cm^2. However, this is not the limit, and apparently the work of separation may even be higher.

Table VI and Figure 6 give a summary of typical values of the work of separation for two different sintering temperatures.

The measured work of separation is accurate to within ± 10%. Surfaces separated from a sintered contact contain pinpoints. The local nature of these pinpoints is evidence that the contact, even the optical one, fuses together only at isolated points on the contact–making surface. As a rule, strong stresses are observed in the sintered–contact region.

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Translated by J. G. Adashko
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