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ON THE FRACTURE OF HIGH-STRENGTH GLASS

It has now been shown that when the defective layer is removed from the surface of glass, the strength of the latter increases substantially. Thus, if the strength of the original industrial glass is 10-30 kg/mm^2, then after appropriate chemical treatment with foamed hydrofluoric acid the glass acquires a strength of 300 kg/mm^2 and more. In work ([1]) a statistical theory of glass fracture was developed, based on the assumption that defects exist both on the surface and in the volume. When the surface layer of glass is removed and appropriate protective coatings are applied, the strength of the glass is determined mainly by various defects located inside the body. Fracture of glass, under a successive increase of load, may begin both from the surface and from within. The fact that fracture of glass may begin from within was known previously as well ([2]). G. M. Bartenev and L. K. Izmailova investigated the fracture of defect-free glass fibers ([3], [4]), which are taken for testing immediately after the spinneret, before winding onto a drum. The strength of such glass fibers does not depend on diameter and length. Fracture of defect-free glass fibers occurs into small pieces, and sometimes into a fine powder, in contrast to fracture into two parts, characteristic of fibers with a defective layer.

A similar fracture was observed by us on specimens of window glass from the Dzerzhinsky Glass Plant (Gus-Khrustalny), obtained by the vertical drawing method. The specimens had the form of a square with a side of 60 mm and were cut with a diamond from glass sheets of size 500×500 mm^2. The thickness of the specimens was from 1.7 to 3.2 mm in different series of experiments. The glass had approximately the following chemical composition: SiO_2 72%, Na_2O 15%, MgO 3%, CaO 8%, Al_2O_3 1.5-2%. Strengthening of the specimens was carried out by removing the defective layer from the surface with foamed hydrofluoric acid in a laboratory apparatus, as a result of which a defective surface layer 100 μ thick was removed. Strength measurements in symmetrical bending were performed on an RM-type machine with a maximum load of 10,000 kg. For

testing the specimens, a square support was used, with a square clear opening of size 50×50 mm^2, and a disk punch 6 mm in diameter. A soft insulation was placed on the support.

The specimens were taken out of the hydrofluoric-acid bath, washed with water and, without being dried, tested in central symmetrical bending. Most of the specimens fractured with a sound resembling a gunshot, with the entire test specimen scattering into small fragments having the appearance of needles with an average thickness from several microns to tens of microns, depending on the magnitude of the rupture stress. If the specimens were dried, such fracture occurred much more rarely. It should be noted that fracture "with explosion" takes place only for glasses obtained from a well-homogenized glass melt.

The mechanism of such fracture "with explosion" was theoretically investigated in work ([5]). By analogy with the picture of propagation of a detonation wave, it may be represented as follows. Under gradual application of load to a glass specimen, potential energy accumulates in it.

the energy of deformation is an analogue of the chemical energy of transformation in an explosion. When a certain critical stress is reached at some point, fracture occurs. From this point a unloading wave propagates in all directions with a velocity equal to the speed of sound in glass. The wave is sustained by the stored potential energy of deformation in those places which it has not yet reached. At the front of this wave, the potential energy of elastic deformation is converted into the surface energy of the crushed glass.

From the known specific surface energy of glass one can determine the size of the glass particles; conversely, from measured values of the sizes of glass fragments one can obtain the specific surface energy.

Let there be a square test plate with side l and thickness h, freely supported along the edges. The plate is bent by a concentrated force P, applied at the center of the square. As a result of fracture, the plate turns into a mass of fragments in the form of long parallelepipeds with square cross section d^2. If the area of the ends of the needles is neglected, then the total area of the fragments will be equal to

$$S = 4hl^2/d. \tag{1}$$

As can be seen, the total area of the needles does not depend on the characteristic length of the needle. The total surface energy of the fractured specimen is equal to

$$W_1 = \frac{4hl^2}{d}T, \tag{2}$$

where T is the specific surface energy for the given material. The potential energy of elastic deformation of the glass specimen is approximately equal to

$$W_2 = P^2 l^2 / 3Eh^3, \tag{3}$$

where E is the Young' s modulus of the material.

Suppose that all the elastic energy of the specimen at the instant immediately preceding fracture has been converted into the surface energy of the fragments, and neglect all kinds of losses. Equating $W_1 = W_2$, we obtain

$$d = 12ETh^4 / P^2. \tag{4}$$

It is evident from this formula that the characteristic size of the fragments (needles) obtained is directly proportional to the Young' s modulus, the specific surface energy, and the fourth power of the plate thickness, and inversely proportional to the square of the concentrated force. The size d of the needles does not depend on the side length of the square plate. Let us give some characteristic data of the experiment described above. For a glass plate ($E = 6 \cdot 10^7$ kg/cm^2) of thickness $h = 0.2$ cm, the value of the breaking force was approximately $P \simeq 500$ kg, while the characteristic transverse size of the needle-like fragments was of the order $d \simeq 5 \cdot 10^{-3}$ cm.

According to formula (4), these data correspond to a value of the specific surface energy of glass of order $T \simeq 10^{-3}$ kg/cm, or, when converted to the cohesion model, $K \simeq \sqrt{\pi ET} \simeq 5 \cdot 10^2$ kg/cm$^{3/2}$. The static cohesion modulus of silicate glass has a value an order of magnitude larger ([6]), $K_{\text{st}} \simeq 6 \cdot 10^3$ kg/cm$^{3/2}$.

Let us recall that under unsteady crack development the cohesion modulus may be considerably smaller than the static value K_{st} ([7]). Wells and Post ([8]) observed a value of the modulus 10 times smaller than K_{st} in the initial moments of unsteady crack development (with further development of the crack, the cohesion modulus increases and reaches K_{st}).

The experiments carried out show that the development of cracks leading to the fracture of specimens made of high-strength glass was unsteady and corresponded to the initial stage of unsteady crack development from primary defects. Precisely such a situation occurs

takes place at the front of the stationary fracture wave, the thickness of which is very small and comparable with the linear dimension of the developing crack and initial defects. Thus, these experiments confirm the theoretical scheme of the phenomenon (5).

Note. It should be emphasized that the energy equation at the jump (1), (6) in (5) has meaning for $D^2 \sim U$, i.e., for $\sigma \sim E$. For $\sigma \ll E$ it becomes an identity. In this practically more realistic case the law of conservation of energy is applicable to the body as a whole. Let us imagine that our one-dimensional body is finite (it occupies the region, say, $0 < x < L$), and that the fracture wave has begun to propagate from both free surfaces of the body ($x = 0$ and

$x = L$). Suppose that the particles of the fractured material do not interact with one another. Then the law of conservation of energy for the body as a whole takes the form

$$\tfrac{1}{2}u_x^2 + \Pi = U.$$

The calculation of the particle sizes from the value of Π is analogous to the preceding one.

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Note: Figure translations are in progress. See original paper for figures.