EFFECT OF BOND STRENGTH ON THE BREAKING STRENGTH OF TWO-LAYER CELLOPHANE FILM MATERIALS

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The effect of bond strength on over-all tensile strength has been investigated in relation to two-layer materials consisting of cellophane film cut in the longitudinal and transverse directions and bonded with polyisobutylene. It is shown that there is a linear correlation between the bond strength and the combination hardening effect. The breaking stress of two-layer materials is higher than that of the individual films. A possible explanation of this effect is proposed.

As a continuation of [1] we have investigated the relation between breaking stress and adhesion for two-layer materials consisting of bonded films with different physicomechanical characteristics but the same chemical composition. The film materials investigated consisted of layers of cellophane cut in the longitudinal and transverse directions and bonded with polyisobutylene (Table 1).

The type of adhesive and the method of obtaining the specimens were the same as previously described in [1]. The strength of the bond between layers was varied by varying the test temperature. Since the cohesive strength of cellophane also varies with the test temperature, the tensile strength was estimated from a characteristic that takes this variation into account. As this characteristic we took the ratio $K_h = \frac{(\sigma_1 - \sigma_0)}{\sigma_0} \cdot 100\%$, where $\sigma_1$ is the breaking stress of the combined material in kgf/cm$^2$, calculated for the true cross section of the material at the given test temperature, and $\sigma_0$ is the breaking stress calculated for the true cross section of the individual film in kgf/cm$^2$ at the same test temperature.

In view of the scatter of the experimental data, in determining the mechanical characteristics we used a statistical method of analyzing the test results. For this purpose the interval of variation was divided into a certain number of steps, after which the number of variants corresponding to each step was calculated. In constructing the distribution curves, values of the measured quantity were plotted along the axis of abscissas and along the ordinate axis values of $N_i/N_{\Delta x}$, where $N_i$ is the number of variants in a given step, $N$ the total number of variants, and $\Delta x$ the width of the step.

The values of $\sigma_0$ (breaking stress of individual film) and $\sigma_1$ (breaking stress of combined materials) correspond to the maxima of the distribution curves, which have the form shown in Fig. 1. In order to calculate the absolute deviation we selected a conventional scale (code). We calculated the arithmetic mean $\bar{x} = \frac{1}{N} \sum_{i=1}^{N} x_i$ and the mean square $\sigma^2 = (1/N) \sum_{i=1}^{N} (x_i - \bar{x})^2$. We then determined the standard deviation $\sigma$.

The absolute deviation was determined as the product of the width of the step and the standard deviation of the distribution. The deviation of the breaking stress from the most probable value corresponding to the maximum of the distribution curve fluctuated in the range ±30 kgf/cm$^2$ for the individual films and in the range ±60–65 kgf/cm$^2$ for the combined materials.
The adhesion of the adhesive to the substrate was determined in peeling tests. The peeling strength was expressed in terms of the peeling force.

![Fig. 3. Temperature dependence of the adhesive strength at different peeling rates: 1) 10 mm/min; 2) 50 mm/min (— cellophane cut in longitudinal direction; — in transverse direction); 3) 264 mm/min; 4) 466 mm/min.](image)

In order to avoid deformation of the films in the peeling process the latter were reinforced with paper of the "imitation parchment" type.

Figure 2 shows the temperature dependence of the strength of the individual and combined film materials at a strain rate of 50 mm/min. The curves describing the temperature dependence of the tensile strength of the combined materials, consisting of cellophane cut in the longitudinal and transverse directions, are similar in character and do not differ essentially from the curves describing the variation of the breaking stress of individual cellophane films. All these curves are exponential in character.

In accordance with the ideas concerning the strength of polymers developed by one of the authors [2, 3], the temperature dependence of the strength of these materials is described by the equation \( \sigma_T = \text{Ae}^{u/RT}v^n \), where \( \text{A} \) is a constant for a given type of specimens, \( u \) is the apparent activation energy of rupture of the chemical bonds, \( v \) is the strain rate, and \( n \) a coefficient determined by the rate of dissipation of stresses at the point of development of the fracture zone. In our opinion it is not the character but the order of the curves that is of greatest interest. In fact, the strength of the combined material reduced to 1 cm² of cross section always exceeds the reduced strength of the films composing that material. It would appear that the breaking stress of a material consisting of three layers (two base layers and a layer of adhesive) ought always to be less than the breaking stress of the starting film, since, apart from its inhomogeneity, the combined material is weakened by the layer of adhesive, whose strength is negligibly small as compared with the strength of the cellophane [1], while the breaking stress of the material is reduced to 1 cm² of cross section of the material as a whole, including that layer.

However, as follows from the experimental data, the breaking stress of the two-layer materials exceeds that of the individual films. The probable explanation is as follows. The failure of any material containing microdefects begins with the generation of microtears [3] at the site of the most dangerous microdefects.

Therefore, in the one-layer (individual) film the appearance of such microtears leads to the rapid failure of the material since in a rigid-chain polymer below the softening point they do not heal [4]. However, in a material consisting of two or more layers, a dangerous microdefect in one layer is protected by the corresponding defect-free part of the adjacent layer. The stresses that become concentrated around this defect when the material is extended are transmitted, if the bond between the layers is sufficiently strong, to the defectless part of the adjacent layer, where they are largely dissipated. Consequently, in this case the stresses must be greater for the microtears to propagate.

![Fig. 4. Relative characteristic \( K_h \) as a function of the bond strength in material: 1) based on cellophane cut in the transverse direction; 2) based on cellophane cut in the longitudinal direction.](image)

Of course, this hardening effect can only take place if the bond between the layers is sufficiently strong.

### Table 1

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Individual cellophane film</th>
<th>Two-layer cellophane material</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>in longitudinal direction</td>
<td>in transverse direction</td>
</tr>
<tr>
<td>Breaking stress, kgf/cm²</td>
<td>1250±30</td>
<td>1060±30</td>
</tr>
<tr>
<td>Relative elongation, %</td>
<td>28±3</td>
<td>120±8</td>
</tr>
</tbody>
</table>

![Table 1](image)