NOTCHED-BUTT TEST FOR THE DETERMINATION OF ADHESION STRENGTH AT BIMATERIAL INTERFACES

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1 Introduction

For many engineering applications, two different materials must be effectively bonded. A common technique to determine the adhesion strength of a polymer-polymer joint is the so-called butt-test. For this test geometry the two materials are connected by a flat and straight interface. Unfortunately, such test produces stress singularities at the edges because of the 90° material wedges at the surface of the materials. It was shown, cf. Ref. [1] that curved interfaces between materials can improve the accuracy to the measurement of the adhesion strength. However, the manufacturing of such specimens is complicated. The curvature must be milled after injection moulding of the first shot and the second material is shot against the curved inlay. Thus the production process of the bimaterial interface is interrupted and the temperatures and other environmental influences may lead to a change of the chemical and physical interactions at the interface. The present paper describes a new and more suitable test geometry for testing adhesion strength at bimaterial interfaces.

2 Analytical and numerical evaluation of stress distribution of the notched butt test

The characterization of the singular stress fields arising at notches and cracks is well known see, for example, Williams [2] and Dempsey and Sinclair [3]. With a polar coordinate system at the corner tip, and assuming separation of variables \((r, \theta)\), the asymptotic 2D elastic stress field close to the free edges of a joint can be written in the form:

\[
\sigma_y(r, \theta) \approx \sum_{m=1}^{M} K_m r^{-\omega_m} f_y^{m} (\theta), (i, j = r, \theta) \tag{1}
\]

where \(K_m\) are the generalized stress intensity factors, \(\omega_m\) is the order of stress singularity (which yields unbounded stresses at \(r \to 0\) if \(0 < \omega_m < 1\)) and \(f_y^{m} (\theta)\) are the characteristic angular shape functions. Due to the fact that this work is focused on the geometry determination of a bimaterial system for stress singularities not to appear, in what follows only a single term, \(M=1\) in (1) will be considered: \(\sigma_y(r, \theta) \approx K r^{-\omega} f_y (\theta).\) There are certain material combinations where \(\omega\) has negative values and this means that no stress singularity appears. In addition to the relation between the moduli, the stress exponent \(\omega\) also depends on the wedge angle between the two materials. To determine the adhesion strength between two materials, a uniform stress distribution or at least finite stresses with a stress concentration somewhere along the interface is a requirement for a reasonable test result. The basic idea of the new notched butt test is to introduce a notch with a particular geometry along the interface between the two materials. After the injection moulding of the specimen a notch with a given radius \(R\) at a certain position \((x_n, y_n)\) along the interface z-axis and also at \((y_n, z_n)\) along the interface x-axis is milled into one of the material components. All along the interface this notch results in a bimaterial wedge as shown in Fig. 2. The wedge angle for the unnotched material \(\theta_1\) is 90° whereas the wedge angle \(\theta_2\) for the notched material must be determined in order to induce a non-singular stress field at the bimaterial interface, thus, a negative exponent \(\omega\) will appear at equation (1). For the material combination considered, the relatively rigid material is polycarbonate (PC) and the soft material is a thermoplastic polyurethane (TPU). For the PC (material 2) the following elastic properties were used: elastic modulus of \(E_2=2200\)
MPa and Poisson’s ratio of $v_2 = 0.41$. TPU behaves linear elastic only at small applied loads with $E_1 = 330$ MPa and Poisson’s ratio of $v_1 = 0.49$. As a first step the power of stress singularity at the edges for the considered TPU-PC composite will be determined and discussed. Using the explicit expressions by Dempsey and Sinclair [3] and introducing the elastic properties of the two materials, the dependence of the power of singularity $\omega$ as a function of the material angle $\theta_2$ can be obtained and is shown in Fig. 2. It becomes clear that as long as the angle $\theta_2 \leq 54^\circ$, $\omega$ is negative for all considered cases (notch at either material and either plane stress or plane strain) and this means that there is no stress singularity and the stresses are uniformly distributed along the interface. For the calculation of the stress distribution along the interface, the 2D finite-element method (ANSYS 12.1®) was used with the assumption that the materials behave linear-elastically. Within the centre of the specimen the stress is more or less homogeneously distributed, whereas towards the edges a stress concentration appears. Within the zone of the notch the normal stress concentration decreases drastically. For the test this decrease has the beneficial consequence that at first there are no stress singularities at the edge. Second it is beneficial that the stresses towards the specimen centre increase, because the influence of possible material effects caused by the injection moulding process disappears in the middle.

3. Experimental determination of adhesion strength between polycarbonate/thermoplastic polyurethane

The bimaterial dog-bone specimens consisting of polycarbonate on the one side and thermoplastic polyurethane on the other side are produced with the bimaterial injection moulding device. A circumferential notch was milled along the interface with a device for notching Charpy impact specimens (DIN EN ISO 179). Notches are milled at 10 specimens within the PC material and also at 10 specimens within the TPU material. For a uniform stress distribution along the whole interface the adhesion strength, $\sigma_d$, is simply given by the critical debonding force, $F_{y,cr}$, from the experiment divided by the cross section, $A_0 = 2a \cdot 2b$ as: $\sigma_d = F_{y,cr} / A_0$. The measured results of all specimens are summarized in Table 1. As was expected, the flat interface specimens provide the lowest value because of the stress singularities at the edges. These high stresses cause local failure at lower applied loads. This is circumvented by the new test.

References


<table>
<thead>
<tr>
<th>Specimen Notch within</th>
<th>Adhesion strength, $\sigma_d$ [MPa]</th>
<th>Standard deviation, [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC</td>
<td>9.88</td>
<td>1.33</td>
</tr>
<tr>
<td>PU</td>
<td>9.11</td>
<td>1.95</td>
</tr>
<tr>
<td>Unnotched</td>
<td>8.16</td>
<td>1.07</td>
</tr>
</tbody>
</table>

Table 1. Measured adhesion strength at the PC/TPU interface.