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Notched-butt test for the determination of adhesion strength at bimaterial interfaces

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Abstract

For the experimental determination of adhesion strength between materials it is desirable to have a uniform stress distribution within the interface of the specimen. The common butt-test with a flat interface between two adhering materials produces stress singularities at the edges of the specimen but shows uniform stress distribution along the interface within the material. To avoid a premature failure at the edge due to the presence of the singularity stress field a notch can be machined, at the interface within one of the materials. For isotropic materials, the notch geometry depends on the Dundurs parameters of the bimaterial system. This notch produces a certain local material angle and eliminates stress singularities at the specimen edges. Analytical and finite-element calculations provide the notch geometry appropriate for uniform stress distribution along the whole interface. The applicability of the test is proven by the determination of adhesion strength between polycarbonate and thermoplastic polyurethane.

1. Introduction

For many engineering applications, two different materials must be effectively bonded. Sometimes high adhesion quality is needed, as for example for handholds of implements but sometimes more or less loose connections are required that guarantee that some relative movement of the materials is allowed. 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, cf. Refs. [1]-[3]. In previous papers [4-7] it was shown that a curved interface between materials can improve the accuracy to the measurement of the adhesion strength. Because of the curvature the maximum normal stress between the components is caused at the pole in the middle of the specimen. 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 Williams [1], Wieghardt [8] and Vasilopoulos [9] for single isotropic corners, Bogy [2] and Dempsey and Sinclair [10-11] for multimaterial isotropic corners, Mantič [12] for single orthotropic corners, Pageau *et al* [13] for single anisotropic corners, Ting [14], Mantič *et al* [15] for multimaterial anisotropic antiplane corners, Barroso *et al* [16], Yin [17] and Hwu *et al.* [18] for multimaterial anisotropic corners.

With a polar coordinate system at the corner tip, and assuming separation of variables (r,θ), the asymptotic 2D elastic stress field close to the free edges of a joint can be written in the form:

$$\sigma_{ij}(r,\theta) \cong \sum_{m=1}^{M} K_m r^{-\omega} f_{ij}^{m}(\theta), \qquad (i,j=r,\theta) \tag{1}$$

where K_m are the generalized stress intensity factors, ω is the order of stress singularity (which yields unbounded stresses at $r\to 0$ if $0<\omega<1$) and $f_{ij}^{m}(\theta)$ 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: $\sigma_{ij}(r,\theta) \cong K r^{-\omega} f_{ij}(\theta)$.

Cases in which ω is complex will not be considered in this work. In a few particular cases, the separation of variables (r,θ) is not possible, see Joseph and Zhang [19] for further information. Logarithmic terms may also appear, see Sinclair [20]. Neither of these two particular situations will be considered in this work. The corresponding transcendental equation for ω in an isotropic bimaterial corner was explicitly given, for example, in Dempsey and Sinclair [11], and is used herein for the calculation of the power of stress singularity. There are certain material combinations where ω has negative values and this means that no stress singularity appears. In addition to the relation between the moduli, the stress exponent ω also depends on the wedge angle between the two materials.

The characteristic angular shape functions for stresses can also be computed easily in the case of isotropic bimaterials, see Barroso *et al* [16].

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. A possible geometry is shown in Fig. 1, in which the notch geometry has been magnified for the sake of clarity. 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 θ_1 is 90 ° whereas the wedge angle θ_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 ω 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 (designed as material 2) the following elastic properties were used for the calculations: elastic modulus of E_2=2200 MPa and Poisson's ratio of ν_2= 0.41. TPU behaves linear elastic only at small applied loads with E_1=330 MPa and Poisson's ratio of ν_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 [11] and introducing the elastic properties of the two materials, the dependence of the power of singularity ω as a function of the material angle θ_2 can be obtained and is shown in Fig. 3. The results for plane strain and generalized plane stress for both notches at TPU and PC were evaluated between 4º and 90º, but results are shown for the transition region, between non-singularity and singularity stresses, between 20º and 90º. Values of $\omega<0$ represent no singularity, while values of $\omega>0$ yield stress singularities. It can be observed from Fig. 3 that for θ_2=90º, either a notch in PC or in TPU gives rise to the same corner geometry and thus, the same value of ω (ω=0.254212 and ω=0.182143 respectively for plane strain and generalized plane stress).

Results in plane strain are more severe: the stress singularities appear at smaller angles in both cases notch in PC (θ_2=63°) and TPU (θ_2=55°), respectively. The angles from which singularities appear in generalized plane stress are respectively (θ_2=65°) for the notch in the PC and (θ_2=69°) for the notch in the TPU.

It becomes clear that as long as the angle $\theta_2 \leq 54°$, ω 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 was used with the assumption that the materials behave linear-elastically. The geometry is similar to that shown in Fig. 1 but reduced to the two-dimensional case in the x-y-plane, where plane stress is assumed. Because of symmetry, only one half of the specimen is considered, i.e. $0 \leq x \leq a$.

The mesh is constructed using 8-node (PLANE82) elements. A fine mesh is used at the edges of the interface between the two materials. The calculations were performed by using ANSYS 12.1®. Since the implementation of ANSYS® is displacement-oriented, displacement-controlled boundary conditions were used. Symmetry implies that nodes on the y-axis should be constrained such that no displacement occurs in the x-direction. The applied displacements at y=h cause the load σ_0 at y=h.

A typical distribution of the normal stress, σ_{yy}, at the bimaterial interface is shown in Fig. 4. 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 singularity 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 disappear in the middle. Especially the overshooting of material one over material two during injection no longer has an influence on the test results, as it would have for the common butt-test.

For a uniform stress distribution along the whole interface the adhesion strength, σ_d, is simply given by the critical debonding force, $F^0_{y,cr}$, from the experiment divided by the cross section, $A_0 = 2a \cdot 2b$, as:

$$\sigma_d = F^0_{y,cr} / A_0 \tag{2}$$

Doing so and considering Fig. 4, which shows stress concentrations higher than one, it becomes clear that this approximation provides a conservative result for adhesion strength. However, if the calculated stress concentrations are considered one obtains for adhesion strength:

$$\sigma_d = \frac{\sigma_{yy,\max}}{\sigma_0} \times \frac{F^0_{y,cr}}{A_0} \tag{3}$$

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 in IPF Dresden. The cross section of the specimens is 4x10 mm. In a first injection process the material above the melting point temperature is injected into the chamber of the tool; after a certain delay (some seconds) the second material is injected against the slightly cooled first material. Physical and chemical interactions are responsible for the adhesion between the two materials at the interface.

A circumferential notch was milled along the interface with a device for notching Charpy impact specimens (DIN EN ISO 179), as seen in Fig. 5.

For our bimaterial composite the cutter with radius of curvature of R= 0.1mm and deepness of D=0.5mm was used. If a deepness D≤R is used, the geometry would be according to that shown in Fig. 1 and 2. The geometry of the milling device with a wedge angle of 45° resulted in a material angle of $\theta_2 = 22.5°$ at the interface. According to the results of the power of stress singularity (see Fig. 3) this angle provides such conditions that there is no stress singularity at the interface around the whole specimen.

In this way notches are milled at 10 specimens within the PC material and also at 10 specimens within the TPU material. These two variants should provide the same adhesion strength values because in both cases the condition of disappearing stress singularities is fulfilled, as also can be seen in Fig. 3. For comparison ten flat interface specimens (common butt test) were also tested in a tensile machine. A typical load-displacement curve of a specimen with notch in polycarbonate is shown in Fig. 6, from which the maximum load is used for the determination of adhesion strength.

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. Bearing in mind that at the interface of the notched specimens there are stress concentrations of about $k = \frac{\sigma_{yy,\max}}{\sigma_0} \approx 1.2$, the adhesion strength for the notched specimens given in Table 1 are even about 20% higher. Taking the mean value of all the notched specimens provides: $\sigma_d = 9.5\ MPa$ and considering the stress concentration provides: $\sigma_d = 11.4\ MPa$. The same material combination was examined with doubly curved interface specimens, as given in Ref. [21], which are also free of stress singularities and the result was $\sigma_d = 11.9\ MPa$.

Summarizing the above described argumentations and experimental experiences it can be concluded that the proposed notched-butt test provides a simple and reliable test to determine the adhesion strength at polymer/polymer interfaces. Using only the maximum load (Eq. (2)) provides a conservative adhesion strength value, because of the stress concentrations in the inner part of the specimen. A main advantage is that the conventional technology of bimaterial injection moulding can be used to measure the quality of interface bonding. Applying the notched-butt test allows the evaluation of variations in the process or material modifications to further optimise the bonding quality at interfaces.

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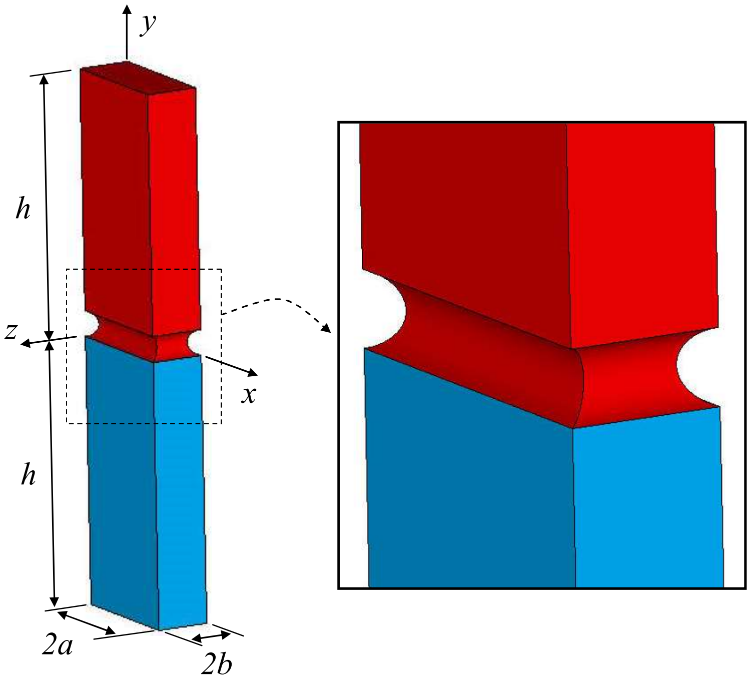

Figure 1: Notched-butt test geometry.

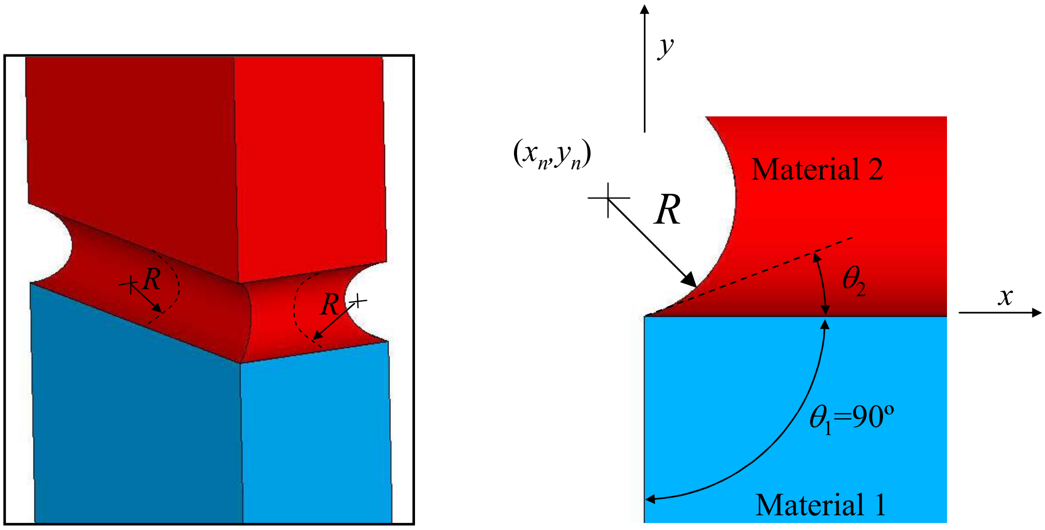

Figure 2: Bimaterial wedge between two polymer materials.

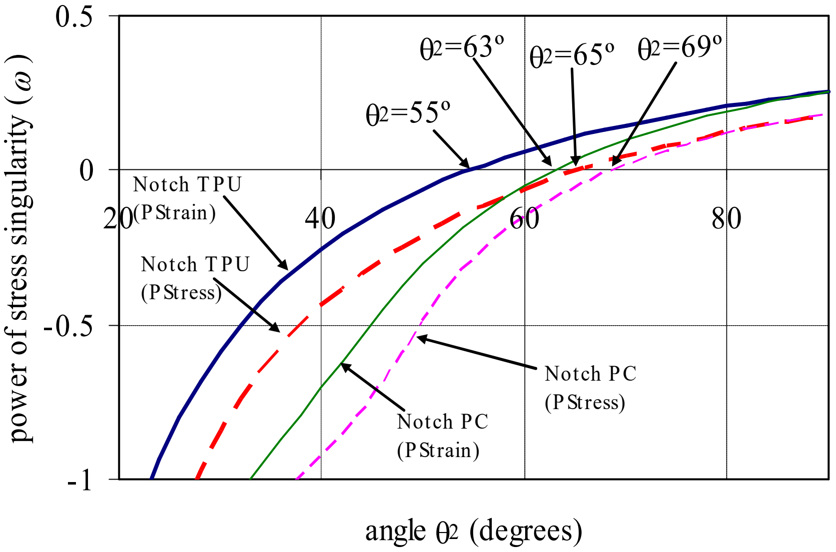

Fig. 3: Power of stress singularity as a function of θ_2 for the two cases of a notch within polycarbonate (PC) or thermoplastic polyurethane (TPU), respectively in plane strain and generalized plane stress.

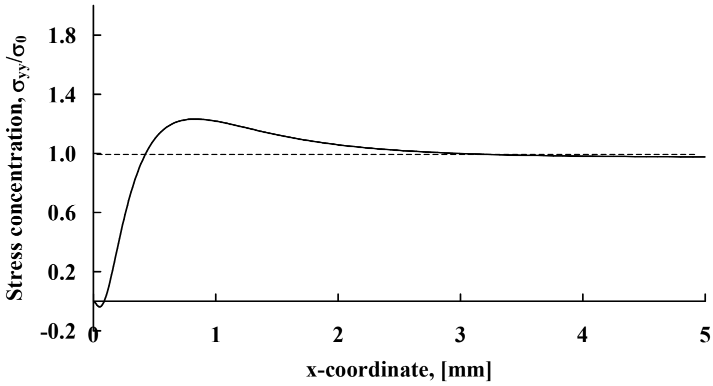

Fig. 4: Normal stress concentration at the bimaterial interface for a notch according to Fig. 2 with the wedge angle of θ_2=14.5° within polycarbonate (PC).

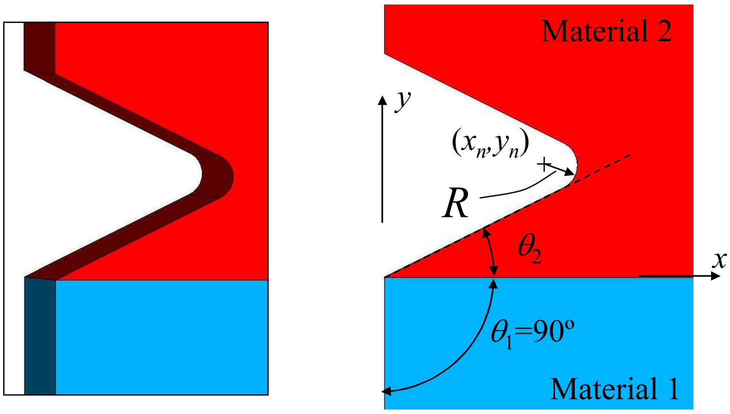

Fig. 5: Notch geometry of tested specimes

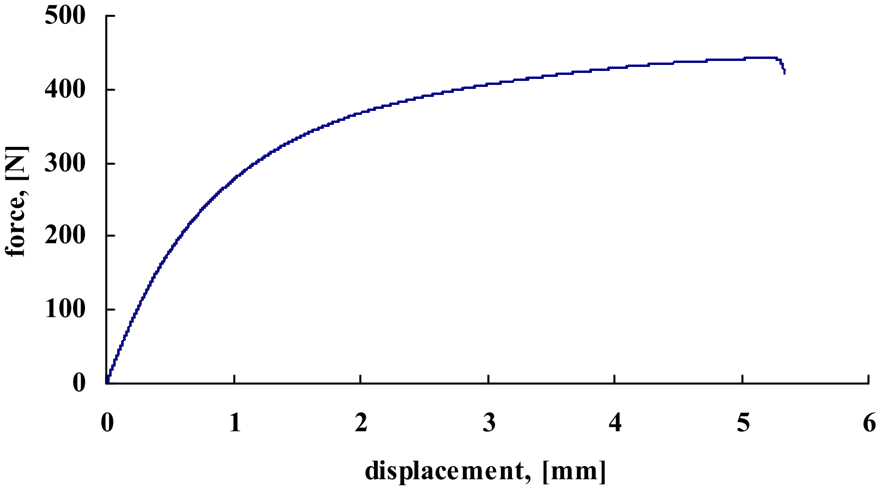

Fig. 6. Load-displacement curve of a specimen with the notch within polycarbonate.

Specimen	**Adhesion strength, σ_d [MPa]**	**Standard deviation, [MPa]**	**Variation coefficient, [MPa]**
Notch within PC	9.88	1.33	0.34
Notch within TPU	9.11	1.95	0.54
Unnotched	8.16	1.07	0.33

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