Evaluation of Tearing Energy of Elastomer Materials

Elastomers · Fracture mechanics · Tearing energy · Landes-Begley method · Pre-conditioning

The Landes-Begley method is applied for the evaluation of tearing energy of quasi-statically strained unfilled and filled elastomers. Two different deformation modes are considered, uniaxial stretching with strip samples and planar stretching with pure shear samples. The results are compared to the predictions of semi-empirical equations often used in fracture mechanics. For both deformation modes, significant deviations from the predictions are found. For the strip samples, a free front factor is used for the tearing energy, which depends on material type and pre-conditioning of filled samples, contrary to the prediction.

Bestimmung der Weiterreißenergie elastomerer Werkstoffe

Elastomere · Bruchmechanik · Weiterreißenergie · Landes-Begley-Methode · Vorkonditionierung

Zur Bestimmung der Weiterreißenergie von quasistatisch gedehnten ungefüllten und gefüllten Elastomeren wird die Methode von Landes und Begley angewendet. Zwei unterschiedliche Deformationsmoden werden betrachtet, uniaxiale Dehnung mit Streifenproben und planare Dehnung mit Pure-Shear-Proben. Die Ergebnisse werden mit den Vorhersagen von semi-empirischen Gleichungen verglichen, die häufig in der Bruchmechanik verwendet werden. Für beide Deformationsmoden werden signifikante Abweichungen von den Voraussagen gefunden. Für die Streifenproben wird ein freier Vorfaktor für die Weiterreißenergie verwendet, der im Gegensatz zur Voraussage vom Materialtyp und der Vorkonditionierung der gefüllten Proben abhängt.

In spite of recent efforts in a physical understanding and quantitative characterization of crack propagation and tear resistance of viscoelastic solids [1-4], there is still a high scientific and technological potential for the development of fracture mechanical models and methods of filler reinforced elastomers, specially due to the strongly non-linear deformation behaviour and stress softening effects [5-7]. The micromechanical mechanisms of crack initiation and propagation in elastomer materials are subject of high scientific interest, because at present it is still not exactly known how these processes start and how they proceed under quasi-static and dynamic loading conditions [7]. Most efforts in this field are based on the fundamental work of Rivlin and Thomas [8].

In the present paper we will consider the tearing energy during quasi-static stretching of strip- and pure shear samples more closely by referring to the method of Landes and Begley [9]. Thereby, the strain energy of notched samples with different cut length is estimated via numerical integration of the measured force-displacement curves. The results are compared to two semi-empirical equations for strip- and pure shear samples, respectively, often used in fracture mechanics. We will demonstrate that for both deformation modes significant deviations from the predictions are obtained.

Materials and experimental details

For experimental investigations unfilled and filled elastomers have been compounded in an industrial type, intermeshing mixer (Werner & Pfleiderer GK 1,5 E). Vulcanization of the samples was performed semi-efficiently with sulfur and accelerator (CBS and DPG) in a heat press up to 90 % of the vulcameter torque maximum (T 90-time). As reinforcing filler, a constant amount (60 phr) of carbon black (N 550) has been used. The basic polymers were a solution-styrene-butadien rubber (S-SBR) with 50 vol.% vinyl and 25 vol.% styrene (VSL 5025-0) and an amorphous ethylen-propylen-dien rubber (EPDM; Keltan 512). All samples were compounded with the processing additives stearic acide and ZnO and protected against aging by IPPD. The ingredients are listed in Table 1.

1 List of ingredients (in phr) of the rubber samples used for experimental investigations.

Sample	EPDM	S-SBR	N550	ZnO	St.-acid	IPPD	DPG	CBS	S
S-SBR		100		3	1	1.5		2.5	1.7
EPDM	100			3	1	1.5	1.5	2.5	1.7
S60N5		100	60	3	1	1.5		2.5	1.7
E60N5	100		60	3	1	1.5	1.5	2.5	1.7

The fracture mechanical investigations were performed at room temperature with two different deformation modes or sample geometries under quasi-static conditions with the tensile tester Zwick 1445. On the one side, notched strip samples (SEN-geometry) of size 100 × 15 mm were tested. On the other side, pure shear samples with different cut length were used. In both cases the cuts were made by a sharp raiser blade. The size of the pure shear samples was 28 × 200 mm. In order to avoid dynamic contributions, the stretching velocity was chosen to be small (20 mm/min), corresponding to a strain rate of $\partial\varepsilon/\partial t \approx 10^{-2}\,s^{-1}$.

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Evaluation of tearing energy by the Landes-Begley method

An important quantity for fracture mechanical investigations is the tearing energy, i.e. the amount of energy required to advance a fracture plane by one unit area. It has been introduced by Griffith in the 1920 s as being the elastic energy available to drive a crack [10]. The tearing energy of quasi-statically strained samples can be determined by using the so-called Landes-Begley method [9]. This method allows for an experimental test of the following two semi-empirical equations for the tearing energy, which are often used in fracture mechanics. For strip samples with a cut on one side, depicted in Figure 1a, it is assumed [7]:

$$T = 2kW_0\,c \quad \text{with} \quad k = \frac{\alpha}{\sqrt{\lambda}} \tag{1}$$

where W_0 is the strain-energy-density stored in the specimen far from the crack tip, c is crack length, λ is stretch ratio and α is a fit parameter. For a pure shear sample geometry, depicted in Figure 1b, the tearing energy is considered to be independent of the crack length [7]:

$$T = W_0\,h_0 \tag{2}$$

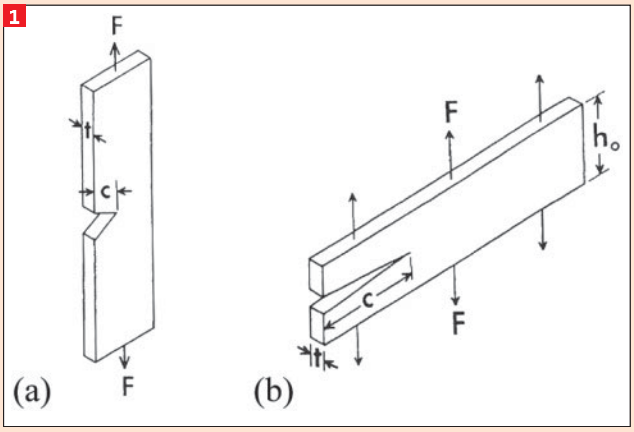
with h_0 being the height of the sample.

The Landes-Begley method [9] starts from the definition of the tearing energy by Griffith in the 1920s as being the elastic energy available to advance the crack area [10]:

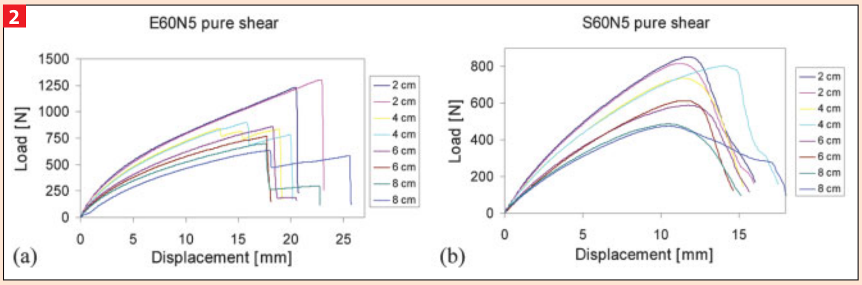
$$T \equiv -\left(\frac{\partial U}{\partial A}\right)_l = -\frac{1}{t}\left(\frac{\partial U}{\partial c}\right)_l \tag{3}$$

Here, U denotes the total strain energy and A is the crack surface area, which is the product of the crack length c and the sample thickness t. The differentiation is carried out at constant strain or sample length l. Equ. (3) takes into account that the elastically stored energy dU is lost when the crack propagates a distance dc leading to the formation of new surface area dA.

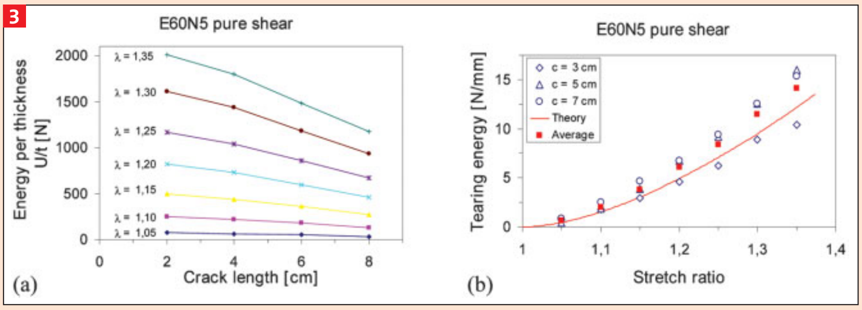
Landes and Begley were among the first to measure T experimentally by referring to the energy release rate definition of T and replacing the differential quotient by a difference quotient [9]. Figures 2 and 3 illustrate their approach. Accordingly, one uses a series of test specimens of the same size, geometry and material, and introduces cuts of various lengths. Then load-displacement curves are measured at the samples with different cut lengths. In the low strain regime, where the cut is not propagating, the area under a given curve corresponding to cut length c is equal to the elastic strain energy U, which differs for the different notch lengths and



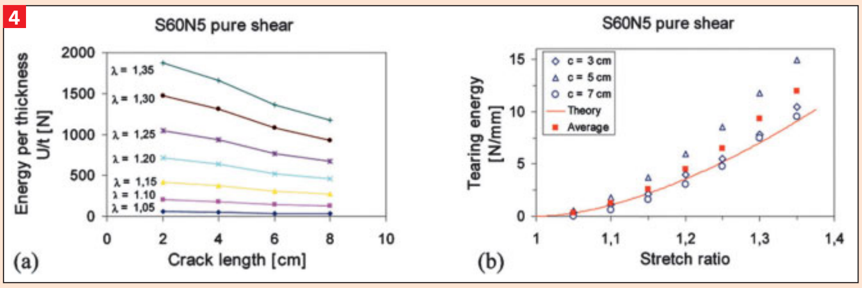
1 Schematic view of two sample stretching modes with single edged notch (SEN), strip samples (a) and pure shear samples (b)



2 Load-displacement curves obtained with pure shear geometry of the EPDM-samples with 50 phr N550 (a) and S-SBR samples with 50 phr N550 (b) at various cut lengths, as indicated



3 Stored energy obtained with pure shear geometry of the EPDM-samples with 50 phr N550 divided by the sample thickness t vs. cut length for various strains (a) and evaluated tearing energy according to Equ. (3) vs. strain (symbols) at various cut lengths, as indicated (b). The line in (b) is calculated by Equ. (2)



4 Stored energy obtained with pure shear geometry of the S-SBR samples with 50 phr N550 divided by the sample thickness t vs. cut length for various strains (a) and evaluated tearing energy according to Equ. (3) vs. strain (symbols) at various cut lengths, as indicated (b). The line in (b) is calculated by Equ. (2)

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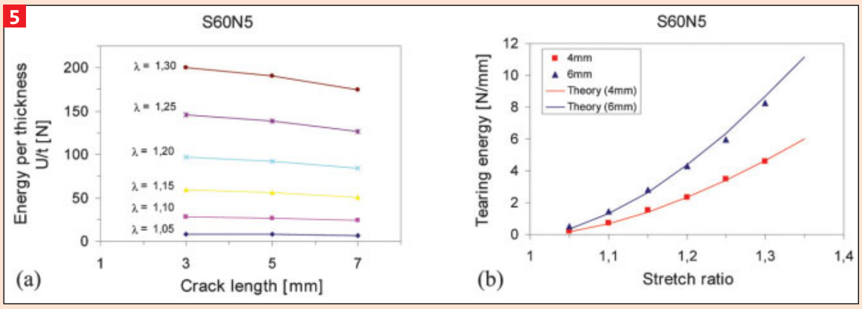

5 Stored energy obtained with strip samples (SEN-geometry) of the S-SBR with 50 phr N550 divided by the sample thickness t vs. cut length for various strains (a) and evaluated tearing energy according to Equ. (3) vs. strain (symbols) at various cut lengths, as indicated (b). The lines in (b) are calculated by Equ. (1) with $\alpha = 2.5$ and $\alpha = 3.1$ for c = 4 mm and 6 mm, respectively

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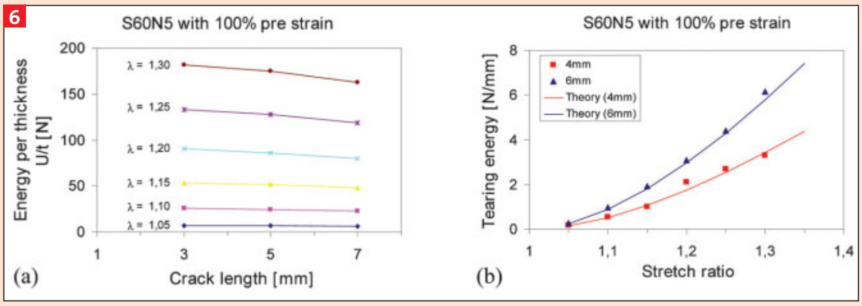

6 Stored energy obtained with 100 % pre-conditioned strip samples (SEN-geometry) of the S-SBR with 50 phr N550 divided by the sample thickness t vs. cut length for various strains (a) and evaluated tearing energy according to Equ. (3) vs. strain (symbols) at various cut lengths, as indicated (b). The lines are calculated by Equ. (1) with $\alpha = 2.0$ and $\alpha = 2.3$ for c = 4 mm and 6 mm, respectively

2 List of fitting parameters α of Equ. (1) obtained with the Landes-Begley evaluation method of the tearing energy from quasi-statically strained strip samples

	c = 4 mm	c = 6 mm
S-SBR	1,2	2,2
EPDM	1,8	1,5
S60N5	2,5	3,1
S60N5 (100 % pre-strain)	2,0	2,3
E60N5	2,3	2,7
E60N5 (100 % pre-strain)	1,7	2,8

strain values (Fig. 2). The difference ΔU found for two samples differing in cut length by Δc defines a difference quotient, which approximates the differential quotient of Equ. (3) if Δc is sufficiently small. This difference quotient $\Delta U/\Delta c \approx \partial U/\partial c$ is estimated via the plots in Figures 3a to 6a as local slope of U vs. c for various cut length c and strain values $\lambda = 1.05$ to 1.35. Finally, the tearing energy T is computed by applying Equ. (3), which leads to the data (symbols) shown in Figures 3b to 6b, i.e. a plot of T versus strain λ at various cut lengths. The latter are compared to the theoretical predictions (lines) obtained with Equs. (1) and (2).

A marked difference between the EPDM- and S-SBR samples with 50 phr N550 is already observed in Figure 2 where results obtained with pure shear sample geometry, illustrated in Figure 1b, are compared. The load of the EPDM samples drops rapidly when the crack propagation starts indicating that the crack propagates rapidly and the crack length increases stepwise. For the S-SBR sample the crack propagation process is more continuous and appears at lower loads. The evaluated tearing energies of the sample E60N5 are somewhat larger than those of the sample S60N5 as depicted in Figures 3b and 4b. In these figures the prediction of Equ. (2) denoted by „theory“ is also inserted, whereby the strain energy density W_0 has been estimated by separate tension measurements with S2-samples. Equ. (2) predicts that the tearing energy obtained from pure shear measurements should be independent of crack length. This is not confirmed by the evaluated data, but a scatter of data points of about 30 % is found for both sample types. Furthermore, the estimated mean tearing energies, denoted „average“ in the legend of Figures 3b and 4b, which have been obtained by calculating the mean slopes over all crack lengths of the data in Figures 3a and 4a, are not in agreement with the „theory“ prediction of Equ. (2).

The data in Figures 5 and 6 have been evaluated from measurements with strip samples illustrated in Figure 1a. The effect of pre-conditioning of the sample S60N5 is demonstrated, resulting in somewhat lower values of the tearing energy for the sample with 100 % pre-strain. This can be understood since the strain energy density of a pre-conditioned sample is lower due to stress softening effects. The “theory” predictions of Equ. (1) are inserted in Figures 5b and 6b as solid lines. It is found to be in fair agreement with the tearing energy in dependence of strain as evaluated by the Landes-Begley method (symbols). Since the tearing energy obtained from strip samples with SEN-geometry depends on notch length, two different branches are found for the mean notch lengths c = 4 mm and 6 mm. However, in both cases depicted in Figures 5b and 6b the fitting parameter α has different values for the two notch lengths c = 4 mm and 6 mm, indicating that the notch lengths dependence of the tearing energy is not described correctly by Equ. (1). Furthermore, it is found that this parameter does not agree with the literature value $\alpha = \pi = 3.14$ [7].

Table 2 summarizes the fitted values of the free parameter α for various samples, confirming that this parameter differs significantly from the value $\alpha = \pi = 3.14$ proposed by Gent [6]. In almost all cases, the fitted α -parameter is smaller than the literature value. Obviously, very low values of α between 1.2 and 2.2 are found for the two unfilled samples S-SBR and EPDM. For the filled samples the value of α seems to vary statistically between 1.7 and 3.1. The large statistical scatter of this parameter indicates that the Landes-Begley method is not very precise. This is mainly due to the large scatter between the different samples necessary for the measurements, since filled rubbers always show a large sample scatter even if they are from the same charge. Obviously, this is also the reason for the observed large scatter of data points in Figures 3b and 4b.

Summary and conclusions

The two semi-empirical Equs. (1) and (2), often used in fracture mechanics for the evaluation of tearing energy of strip samples and pure shear samples, respectively, have

been tested by applying the Landes-Begley method to quasi-statically stretched unfilled and filled elastomers (SEN-geometry). For the strip samples, a free front factor has been introduced as a fit parameter in Equ. (1). This parameter differs significantly from the value $\alpha = \pi = 3.14$ proposed by Gent [6]. In almost all cases, the fitted α -parameter is found to be smaller than this value, depending on the sample type and pre-conditioning of the samples. Very low values of α between 1.2 and 2.2 are obtained for the two unfilled S-SBR and EPDM samples. For the filled samples the value of α seems to vary statistically between 1.7 and 3.1.
Equ. (2) predicts that the tearing energy obtained from pure shear measurements should be independent of crack length. This could not be confirmed by the evaluated data, but significant deviations appear and a scatter of data points of more than 30 % is found. However, it must be noted that due to the large scatter between the different samples necessary for the measurements, the Landes-Begley method is not very precise, since filled rubbers always show a large sample scatter even if they are from the same charge.

Acknowledgements

This work was supported by the Deutsche Forschungsgemeinschaft (DFG). Helpful discussions with the members of the DFG research unit FOR 597 and its speaker Prof. G. Heinrich (IPF Dresden) are highly appreciated.

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