The Test Frequency Dependence of the Fatigue Behavior of Elastomers

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ABSTRACT

In engineering applications elastomers are frequently exposed to complex combinations of cyclic mechanical loads. A better understanding of the material resistance against crack initiation and propagation becomes of increasing practical importance. Engineered elastomer parts and components are loaded over a very wide range of loading frequency (1 to 10^5 Hz) and reveal significantly different failure fatigue behaviour in the low and in the high frequency range, respectively. Furthermore, it is also a well-known phenomenon that viscoelastic materials may reveal a hysteretic type heating during cyclic loading. Fatigue tests were performed on two elastomer types using a high rate servohydraulic test system. A pure shear specimen configuration with razor blade precrack was used in this study. The test frequency was varied between 0.2 and 50 Hz. The tearing energy was calculated based on the strain energy density data, which were determined using the stress-strain hysteric curves. In addition during the cyclic loading the specimen temperature was measured. The crack growth rate was found to depend on the test frequency. With increasing test frequency the crack growth rate increases and then decreases with the same energy input. This is a complex result of the balance of two competitive effects, the reduced mobility and the hysteretic heating.

Introduction

The fatigue behavior of rubber has widely been characterized using fracture mechanics methods [1, 3-5]. The tearing energy based approach proposed by Rivlin and Thomas [1, 2, 6 and 7] has successfully been used in the last decades for fatigue testing of elastomeric materials [7-9]. Although many investigators demonstrated [2 - 5] that the tearing energy is independent from the specimen size and geometry, there is still a debate about the applicability of the tearing energy concept to estimate the life time of real components and the usage in engineering design procedures.

Furthermore, it is also a well-known phenomenon that elastomeric materials may reveal a hysteretic type heating during cyclic loading [2]. This temperature increase is influenced by various factors, i.e., loading frequency, amplitude, the viscoelastic loss, the heat capacity and conductivity of the elastomer type [4] and may affect the overall fatigue response of these materials.

Hence the main objectives of this paper are: (1) to develop and implement adequate test methods and data reduction schemes to determine the test frequency dependence of the crack initiation and growth resistance of elastomers under cyclic (fatigue) loading conditions and (2) to investigate the hysteretic heating process in elastomers during cyclic loading with various amplitudes.

Experimental

Materials
The test frequency dependence of the fatigue behavior of two different elastomers, an ethylene-propylene-diene (EPDM) and a styrol-butadien rubber (SBR) grade have been investigated. The materials were produced by Semperit Technische Produkte Ges.m.b.H. & Co KG, (Wimpassing, Austria) and supplied as test specimens. The average Shore A hardness value is 70 for SBR and 50 for the EPDM type.

Specimen Configuration
The specimen geometry used for these investigations was a modification of the well known pure shear geometry which is frequently used to characterize the fatigue behavior of elastomers. The so-called faint waist pure shear (FWPS) specimen configuration is shown in Fig. 1. To avoid the pull-out of the specimens from the fixture a positive fit shoulder and to keep the crack growth in-plane as long as possible a faint waist is applied in the specimen. The specimens were precracked on one side (single edge notched specimens,

SEN) by introducing a 15 mm long cut using a cutting device with a fresh razor blade allowing for a reproducible cut geometry. While a perfect pure shear specimen would have an infinitely high width-to-height ratio, *W/h*, only a finite *W/h*-ratio can be realized in practice. According to Yeoh [10], this *W/h*-ratio should be larger than 6 to be in good agreement with the theoretical pure shear state of stress. Due to its special geometry our FWPS specimen fulfils the requirement of the pure shear state (i.e., the actual W/h-ratio is of 12.5).

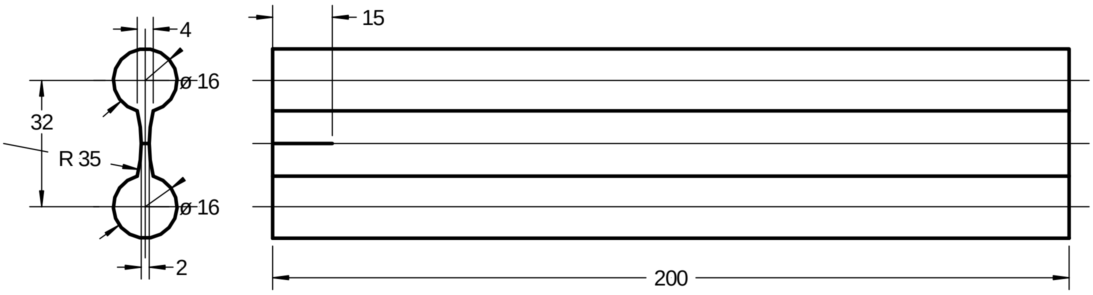


Fig. 1: Geometry of the single edge notched faint waist pure shear (SEN-FWPS) specimens.

Test Conditions

All tests were run under displacement control on a servo-hydraulic test system (an MTS 831.59 Polymer Test System, MTS Systems Co., MN, USA) using FWPS-SEN specimens. A single specimen method was used to generate the crack growth kinetics diagrams. The loading waveform was sine and the test frequency was varied in a range of more than two decades (0.25 Hz, 2 Hz, 5 Hz, 10 Hz, 20 Hz and 50 Hz). The strain R_ε-ratio was kept constant at 0, which means that the specimens were completely unloaded after every cycle. During the test the amplitude was gradually increased from 0.3 mm to 2.8 mm for SBR and from 0.5 mm to 7.1 mm for EPDM, respectively (see Fig. 2). In order to maintain the fatigue character of the test, 10^4 cycles were carried out at each displacement level.

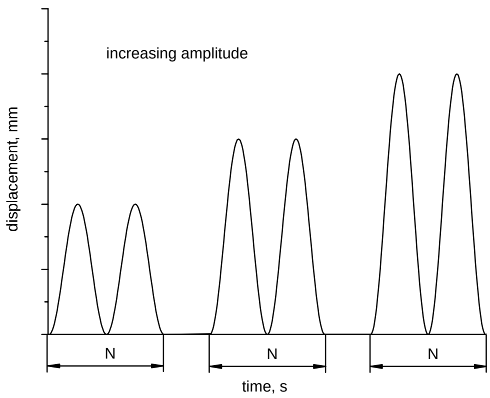


Fig. 2: Amplitude sequence for the single specimen fatigue test method.

Data Reduction

The tearing energy can easily be calculated for the pure shear geometry using the following equation;

$$T = Wh \tag{1}$$

where *W* is the strain energy density and h is the initial height of the specimen. The strain energy density is calculated as follows:

$$W = \int_{\varepsilon_0}^{\varepsilon_{max}} \sigma \, d\varepsilon \tag{2}$$

where σ is the nominal stress and ε is the nominal strain.

Equation 1 illustrates one main advantage of the pure shear geometry, T is independent of the crack length and no geometry correction factor is necessary in order to calculate it [10].

The global force and displacement values were continuously measured during the cyclic loading and the nominal stress and nominal strain values were calculated. These data are used to generate hysteretic plots. To take the reduction of effective area, the stress σ is calculated according to Equ. 4. The displacement is also normalized to strain ε (Equ. 5) or to extension ratio λ .

$$\sigma = \frac{F}{t(w-c)} \tag{3}$$

$$\varepsilon = \frac{l - l_0}{l_0} \tag{4}$$

The stretch ratio, λ is calculated as:

$$\lambda = \varepsilon + 1 \tag{5}$$

The strain energy, *U* is calculated in the form (only the positive values at *F* > 0 are used to calculate the energy)

$$U = \int \{F | F \geq 0\} ds \tag{6}$$

the tearing energy, *T* is calculated as

$$T = \frac{U}{t(w-c)} \tag{7}$$

The crack length was measured after each displacement level using a traveling microscope and the crack growth rate was calculated.

$$crack\ growth\ rate = \frac{dc}{dN} \tag{8}$$

where ΔN is the number of cycles (10^4) and *dc* is the increase in crack length.

In order to characterize the influence of test frequency on the hysteretic heating a point type infrared sensor Optris CT (Optris Gmbh, Berlin, D) was used. The temperature range of the sensor is from 0 °C to 300 °C. Specimen surface temperature values were measured in two locations (near field and far field) in a small area in a non-contact way. The exact location of the point sensors was assigned based on the results of a previous full-field temperature analysis by a thermography system (Altair, Cedip, F). It must be emphasized, however, that due to the global energy character of the tearing energy method the temperature change was also measured in the far field specimen ligament.

The maximum temperature of the specimen ligament, T_{max}^{l}, is measured at the end of each amplitude set of 10^4 cycles as follows,

$$T_{\max} = T\big|_{N=10^4} \tag{9}$$

The temperature increase per amplitude set, ΔT, is the difference between T_{max} and the temperature after 500 cycles.

$$\Delta T = T\big|_{N=10^4} - T\big|_{N=500} \tag{10}$$

Results

Hysteretic curves and crack length development

The cyclic stress-extension ratio curves of both materials are shown in Fig. 3. The stress vs. extension ratio diagrams take into account the reduction of the effective specimen cross section due to crack growth. While SBR revealed a significantly higher stiffness than EPDM the hysteretic behavior was nearly the same.

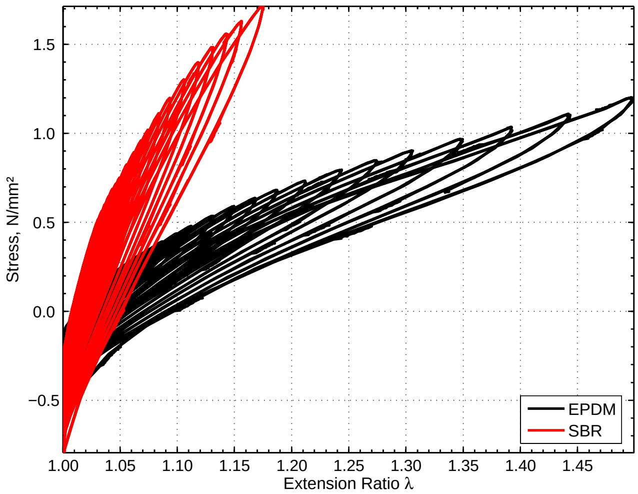


Fig. 3: Cyclic stress vs. extension ratio curves for SBR and EPDM at a test frequency of 5 Hz.

The change of the crack length in the FWPS specimen during the fatigue test is plotted against the number of cycles in Fig. 4. The crack growth rate was calculated based on these diagrams.

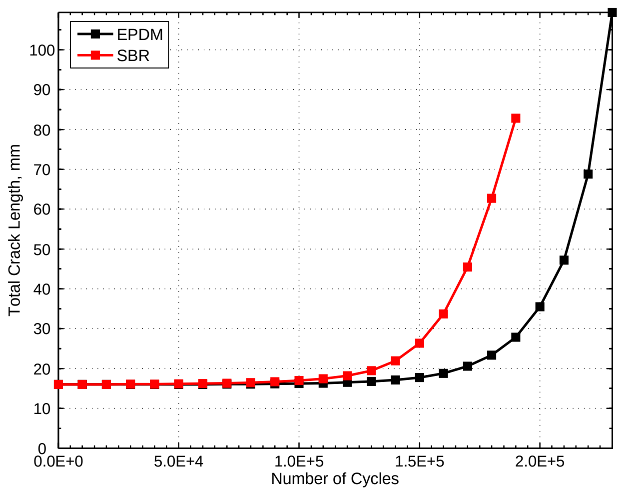


Fig. 4: Crack length vs. number of cycles curves for SBR and EPDM at a test frequency of 5 Hz.

The strain amplitude dependence of the crack length is shown in Fig. 5 for both materials (a) at 5 Hz and (b) at 50 Hz test frequency. The crack starts to grow at significantly higher amplitudes for the EPDM elastomer than for the SBR. Furthermore, while the crack growth was the same at 5 and 50 Hz for SBR the EPDM reveal a significantly higher frequency dependence.

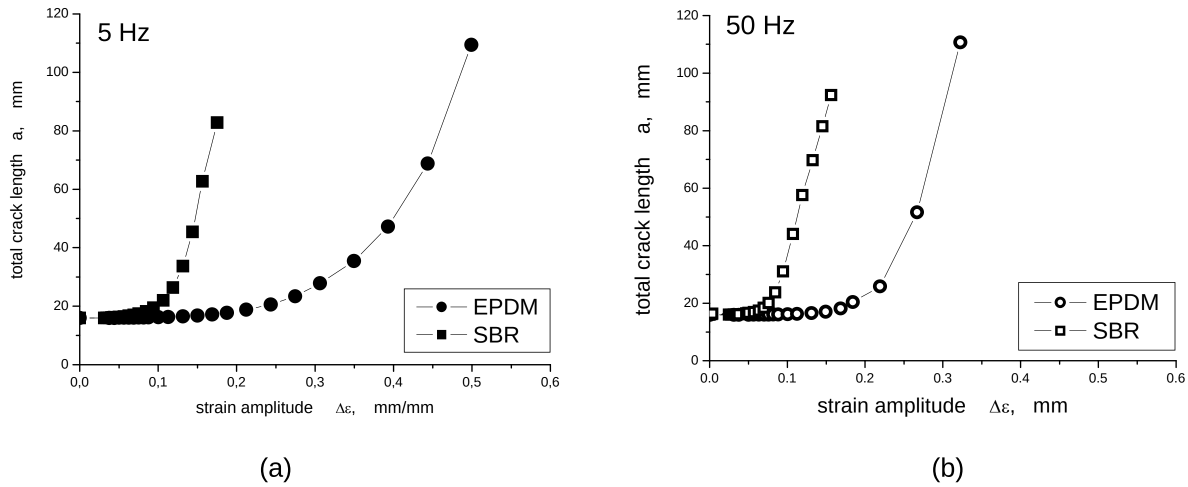


Fig. 5: Crack length vs. strain amplitude curves for SBR and EPDM at a test frequency of 5 Hz (a)and at 50 Hz (b).

Influence of test frequency on the fatigue properties

The crack growth kinetics curves (*da/dN* vs. *T*) for both materials measured over a wide frequency range are shown in Figs. 6a and b, respectively.

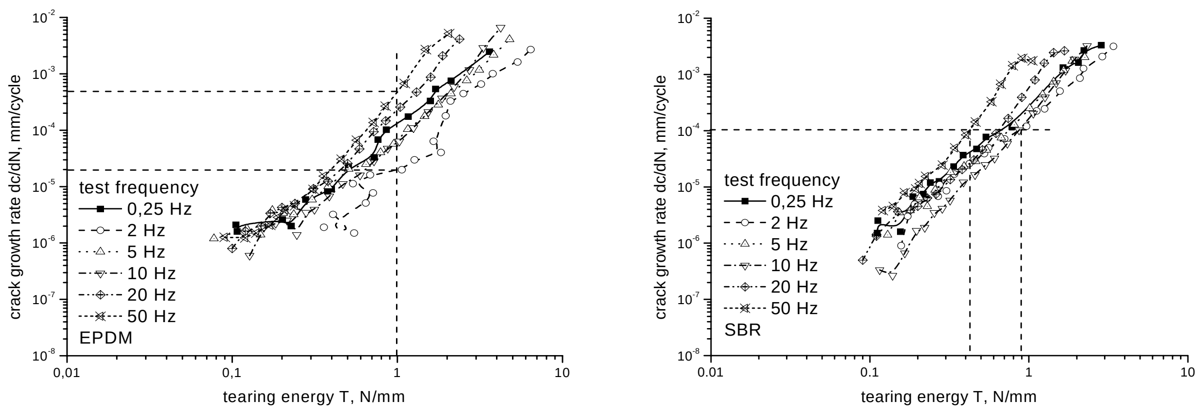
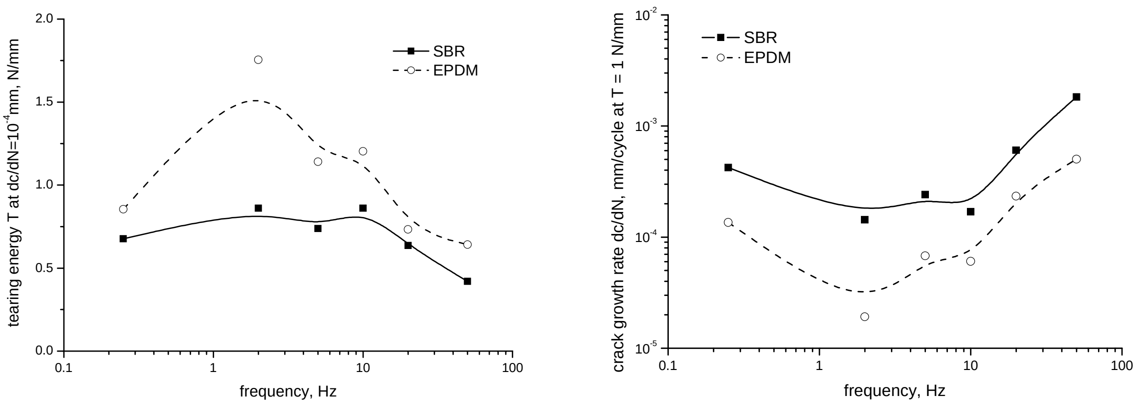


Fig. 6: Crack growth rate vs. tearing energy for the SBR rubber (a)and for the EPDM rubber (b). The fatigue tests were carried out at frequencies from 0.25 to 50 Hz.

To gain more insight into the frequency dependence of the fatigue behavior of the rubber types investigated the tearing energy values, necessary to achieve a crack growth rate of 10^{-4} mm/cycle is shown in Fig 7a. The curves for both rubber types reveal a maximum between 2 and 5 Hz. The opposite tendency – both curves reveal a minimum - is evident if the crack growth rate values at a given tearing energy of 1 N/mm is plotted against the test frequency (see Fig. 7b). It is mentioned, however, that the minimum/maximum of these curves is in the same frequency range.



(a) (b)

Fig. 7: Tearing energy necessary to achieve a crack growth rate of 10^{-4} mm/cycle (a) and at a tearing energy of 1 N/mm (b) for both the EPDM and the SBR rubber.

Influence of mechanical loading on the specimen temperature

The specimen temperature distribution around the crack tip and in the specimen ligament at a given test amplitude can be seen in Fig. 8a (the surface temperature is proportional to the gray scale intensity of the image). The specimen temperature distribution in the mid-section of the specimen is plotted in Fig. 8b.

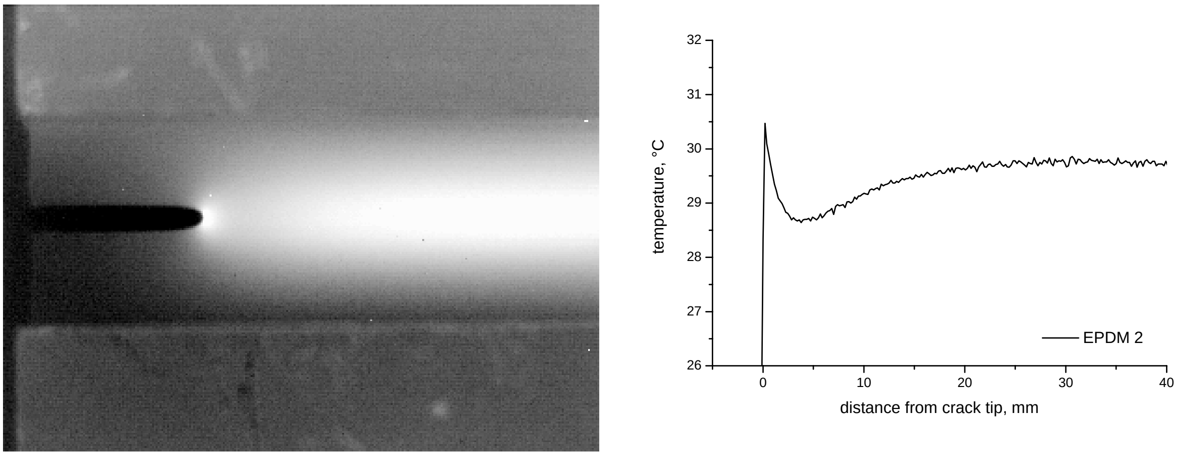


Fig. 8: Specimen surface temperature for SBR at 2.0 mm loading amplitude and 10 Hz frequency; the image shows the temperature distribution after 15 s of cyclic loading (a) and the temperature distribution in the mid-section after 15 s of cyclic loading (b), beginning at the crack tip.

The specimen temperature history for a loading sequence with same amplitude is plotted in Fig. 9. During the loading of the specimen the temperature increases and approaches a stationary value. The temperature difference between the start temperature and the end temperature was found to increase with increasing test amplitude. Furthermore, the overall specimen temperature history is plotted in Figs. 10a and 10b. Due to the increasing amplitudes during the test the specimen temperature increases until the end of the test. The vertical drops are the timely positions of the crack length measurement, where the loading has to be discontinued and the test amplitude was increased. Moreover, the overall specimen temperature history exhibits nearly a linear function of the loading amplitude. This is true for both materials and for all frequencies, as it can be seen in Figs. 11a and 11b. With increasing test frequency the temperature increase is significant. While, along with identical test amplitudes the EPDM specimens reveal lower specimen temperatures, the absolute specimen temperatures are higher and reach the 100 °C.

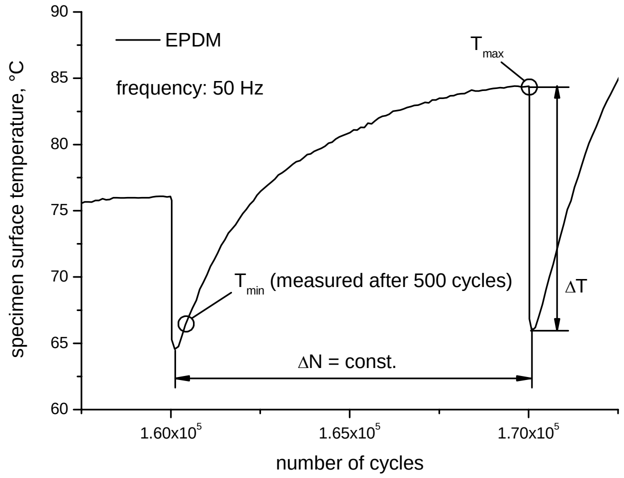
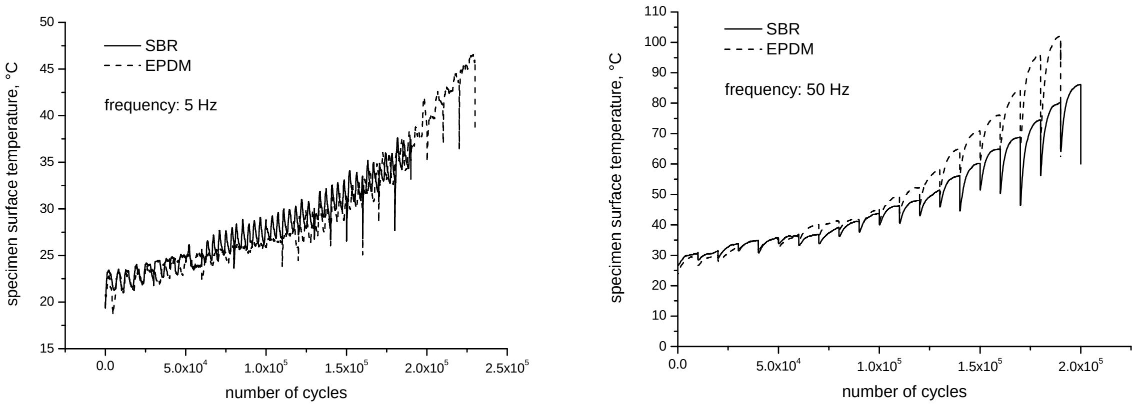
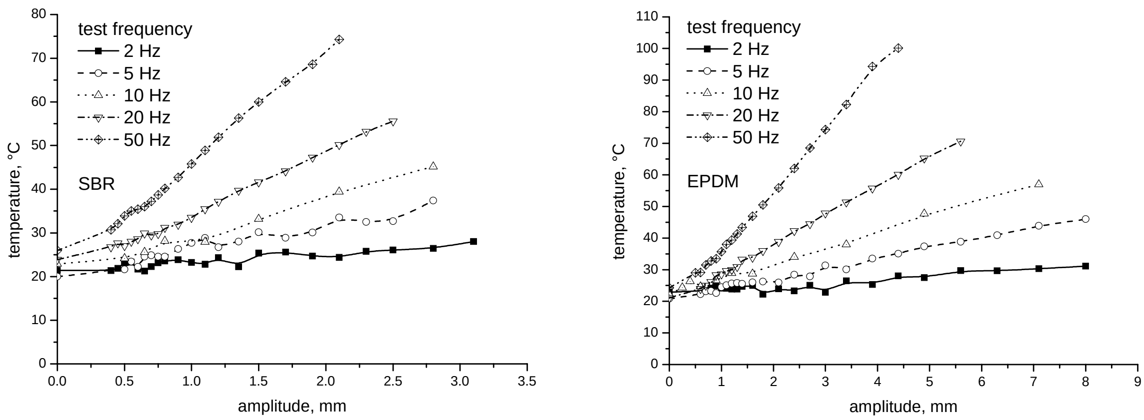


Fig. 9: Temperature development for one set of loading cycles for EPDM at 50 Hz test frequency.



(a) (b)

Fig. 10: Temperature development for a complete fatigue test for EPDM and SBR at 5 Hz test frequency (a) and at 50 Hz test frequency (b).



(a) (b)

Fig. 11: Temperature vs. loading amplitude for the SBR rubber (a) and for the EPDM rubber (b). The measurements were carried out at frequencies from 0.25 to 50 Hz.

Summary and Conclusion

Fatigue crack growth experiments were performed on two elastomer types using pure shear specimen configuration over a wide test frequency range. The crack growth behavior was characterized using tearing energy vs. crack growth rate diagrams. Many effects influencing these diagrams were identified. Although, the crack growth rate clearly depends on the test frequency no unequivocal tendency was identified. At a specific tearing energy the crack growth rate reveal a minimum value in the test frequency range of 2 to 5 Hz. At lower and at higher test frequencies the same energy input leads to a faster crack growth.

Furthermore, the specimen surface temperature was found to increase continuously with increasing test frequency and to reach nearly 100 °C at higher amplitudes. This temperature rise becomes significant for test frequencies higher than 2 (5) Hz. This fact should lead to increased precaution for hysteretic heating at rubber fatigue testing. The test frequency decision has to be taken very carefully if an isothermal situation has to be achieved. A test frequency up to about 2 Hz would mean nearly isothermal condition. In this case, however, the testing time would be very long and the costs are very high. However, fatigue tests at higher frequencies may lead to results where the interpretation of the data became difficult. Test frequencies in the range of 5 Hz would represent a reasonable compromise.

Moreover, real engineering components may be exposed to high or very high frequency cyclic loads. In this case, it is possible, however, to perform fatigue characterization testing in the range of the relevant service frequencies of the components. The main limit is the frequency range (frequency/amplitude characteristic) of the test system. At the actual point of knowledge the prediction of fatigue behavior is, due to its complex combination of influence factors, very difficult. The extrapolation to higher frequencies is even more challenging. Here also thermal properties have to be taken into account, which may lead to questionable accuracy of the predictions. The hysteretic temperature increase must be seen as an intrinsic material response to the mechanical load, which reflects the real situation and should not simply be eliminated by artificial test parameters, even if it is essential to keep in mind the temperature as a source of other influences.

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