Heat build-up of rubbers during cyclic loading

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ABSTRACT: The unique mechanical properties of rubbers make them suitable for applications in which cyclic loadings are involved and hence, fatigue characterization represents a fundamental requirement for these materials. However, due to the high hysteretic losses present in such materials, a significant heat generation is present. This effect in combination with the low thermal conductivity, leads to a considerable increase of temperature in the rubber components, which is commonly referred as heat build-up. In order to avoid such temperature rises, low frequencies or small thickness can be used during material characterization. However, in real applications, limiting these two parameters it is not always possible and hence, a proper analysis of this phenomenon is required. In order to have more details about heat build-up, two different rubbers were tested under cyclic loading and surface temperatures were evaluated and compared taking into account the energy dissipation involved in the loading processes. In particular two specimen geometries were considered, one used for the characterization of fatigue crack nucleation and one used for fatigue crack growth analysis. For the first case, 3D dumbbell specimens were cyclically loaded with a sine wave at different testing conditions and the surface temperatures were monitored with an IR sensor. For the second case, pure shear specimens were cyclically loaded and the surface temperatures were monitored using both an IR sensor and an IR camera. In this latter case, the impact of the presence of a crack on the surface temperature was also considered. Moreover, starting from the heat equation, the temperature profiles along the thickness for both specimen geometries were considered. In order to have a proper description of the temperature distribution, thermal conductivity for both materials were evaluated as well using two different techniques. The analysis of the temperature distribution in the volume is important to distinguish between fatigue and thermal failure. With the obtained data, a further description of heat build-up in rubbers can be provided, contributing in the differentiation between failures related to fatigue and the ones related to local temperature increase.

1 INTRODUCTION

Fatigue characterization is of fundamental importance when dealing with rubbers. In fact, due to their mechanical behavior, rubber products are used in applications in which cyclic loadings are involved and therefore, fatigue represents one of the most common reason of failure for these components (Gent, 2012). The fatigue analyses of rubbers are usually carried out exploiting two different approaches: crack nucleation and crack growth. The first one is based on continuum mechanics and deals with the nucleation and growth of cracks, while the second is focused on the growth of pre-existing cracks making use of fracture mechanics tools (Mars & Fatemi, 2002).

Under cyclic loadings, rubbers show high level of heat generation as a consequence of dissipation mechanisms due to the viscoelastic nature of elastomers and due to the presence of fillers (Medalia, 2011). However, the dissipated heat cannot be transferred fast enough to the surrounding environment due to the low thermal conductivity of rubbers (Gschwandl et al., 2019), inducing a temperature increase in the rubber components. This phenomenon is commonly referred as heat build-up and its degree strongly depends on the material stiffness, on the frequency of oscillation, on the loading amplitude and on the thickness of the component (Gent, 2012).

Due to heat build-up, the temperature of the specimen under cyclic loading could reach high levels even for tests performed at room temperature, affecting the results of the fatigue characterization. In fact, temperature has a relevant effect on fracture (Schrittesser et al., 2012) and on the fatigue properties of rubber: it has been shown that higher temperatures result in faster crack growth and lower fatigue life (Lake & Lindley, 1964; Young, 1986). It seems therefore indispensable for a proper material characterization, the analysis of heat build-up and its consequences in terms of temperature increases. In order to achieve these goals, two different rubbers were tested under cyclic loading using two geometries and their surface temperatures were monitored. The chosen geometries were 3D dumbbell, used for crack nucleation approach (Arbeiter et al., 2015) and pure shear geometry, used for crack growth approach (Schieppati et al., 2018). Moreover, for pure shear geometry, the temperature was monitored with an IR camera. Finally, the thermal conductivity of the materials were tested using two different techniques, giving the possibility to estimate the temperature profile along the thickness, providing further insights in the self-heating of rubbers.

2 EXPERIMENTAL PART

2.1 *Material*

The materials used for this research are acrylonitrile butadiene rubber (NBR) highly filled with carbon black and a blend of styrene butadiene rubber (SBR), butadiene rubber (BR) and natural rubber (NR), highly filled with two grades of carbon black. Due to confidentially, no additional information about the formulations can be given. For sake of simplicity, from now on the first material will be called Material A and the second Material B.

2.2 *Thermal conductivity*

Thermal conductivity measurements of both materials were carried out using two different methods: a guarded heat method using a DTD300 machine by TA instruments and a laser flash method (LFA) with a LFA467 Hyperflash machine by Netzsch. It is worth noting that the actual measurement from the LFA method is thermal diffusivity. The thermal conductivity can be retrieved by knowing the density and specific heat of the material. The specific heat was measured with a DSC6000 by Perkin Elmer while the density was measured using a XS205 Dual Range Analytical Balance by Mettler Toledo. The measurements for thermal conductivity were carried out between 30 °C and 130 °C, every 10 °C. For the measurements carried out with the first method, specimens with thickness of 2 mm were used, while for the second method specimens 1 mm thick were chosen.

2.3 *Surface temperature*

The evolution of surface temperature during cyclic loading was measured using a CT IR sensor by Optris. The measurements were recorded during fatigue characterization using two different specimen geometry, pure shear and 3D dumbbell. These geometries are normally used for fatigue characterization of crack growth and crack nucleation respectively. The dimension of the pure shear specimens were 16 mm of height, 200 mm of width (width to height ratio 1/12.5) and thickness of 4 mm. The dumbbell specimens were cylindrical with a diameter of 15 mm and a gauge height of 20 mm. Fatigue tests were implemented using a MTS 858 Table Top System testing machine. Both materials were tested using a 3D dumbbell geometry at 1 and 4 Hz; the tests were conducted in force control using a load ratio of 0.1 and a maximum force of 560 N. For pure shear geometry, both materials were tested in displacement control using a load ratio R_ε= 0.5 at a maximum strain of 10 %; the used frequencies were 0.25, 1, 4 and 10 Hz. Surface temperatures for pure shear specimen at different strain level were recorded also with an infrared camera by FLIR Titanium SC750).

3 RESULTS AND DISCUSSION

3.1 *Thermal conductivity*

Rubbers are poor conductors of heat and the low thermal conductivity greatly determines the temperature rise upon loading. Therefore, the values of thermal conductivity of both materials were characterized by means of two different techniques in the range of possible utilization of rubber components. In Figure 1 and 2 are reported the thermal conductivity as a function of temperature and for both measurement techniques for material A and Material B respectively. Both methods reveal results in very good agreement along the investigated temperature range. Compared to the guarded heated method the results for the laser flash method are more scattered, since more measurements are necessary for obtaining these results. Moreover, it is worth notice that

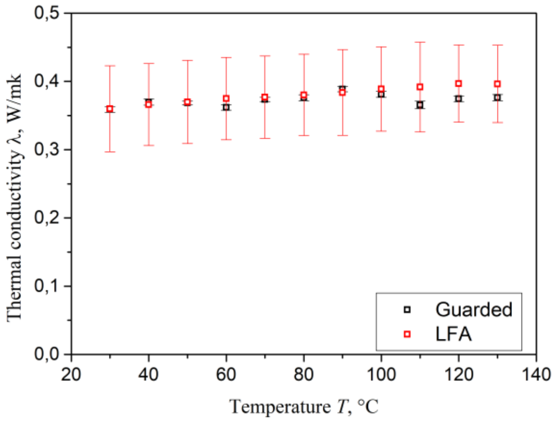

Figure 1 Values of thermal conductivity for Material A between 30 and 130 °C measured with two different techniques: in black the data obtained with the guarded heat method and in red the one obtained with the laser flash method.

the values remain almost constant along the tested range of temperature. The average values across all the range of temperature for the two methods are reported in Table 1.

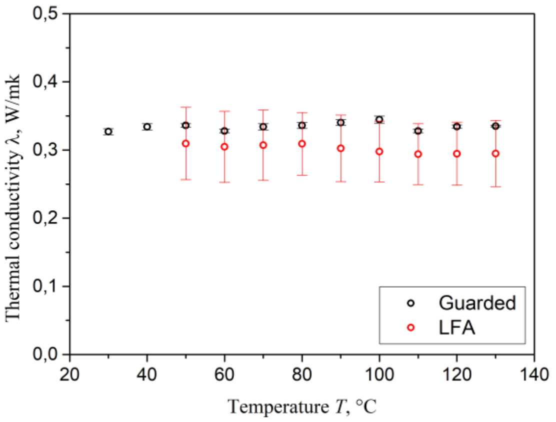

Figure 2 Values of thermal conductivity for Material B between 30 and 130 °C measured with two different techniques: in black the data obtained with the guarded heat method and in red the one obtained with the laser flash method.

Table 1. Average values of thermal conductivity of both materials along the temperature range obtained with guarded heat and laser flash methods.

Method	Material A		Material B	
	λ (W/mK)		λ (W/mK)	
Guarded heat	0.372	±0.004	0.381	±0.061
Laser flash	0.334	±0.004	0.302	±0.048

3.2 *Surface temperature*

As discussed in the previous paragraph, rubbers possess low thermal conductivity and therefore the heat generated under cyclic loading cannot be transferred fast enough to the surrounding environment, resulting in an increase in temperature. The temperature increase is a function of the stiffness of the material and of the characteristic of the oscillating loading, i.e. frequency and amplitude. Moreover, an increase in the thickness of the components will result in higher heat build-up and temperature. In Figure 3, the hysteresis curves are reported for both materials at a cycle number of 10000 cycles. From the curves, it is possible to see the difference in the material behavior: material A (black) is much more stiff with a relative small hysteresis while material B (red) show a much softer behavior and high dissipated energy (area inside the curve). In Figure 4 are reported the plots of the surface temperature evolution upon loading as a function of number of cycles for all tested conditions. During the first cycles, the temperature raised due to the internal heat generation, which is higher than the rate of cooling due to the external environment. As the temperature increased, the driving force for cooling increased until the rate of cooling became equal to the rate of internal heat generation. As a result, the temperature showed a plateau value, which was stable during cycles. Similar results were found for pure shear geometry. (Schieppati et al., 2018). As expected, the plateau temperatures for material B were higher for both frequencies, since the dissipation of energy was higher for this compound. In Table 2, the values of the plateau surface temperature and the relative temperature increases are reported. As expected, higher frequencies resulted in higher surface temperature. However, it is evident that even a small change of frequency results in big differences of temperature increase for dumbbell specimens. Beside the test of material A at 1 Hz, the increase in temperature for the other testing conditions is high and therefore it is not possible to neglect the temperature effect during fatigue analysis.

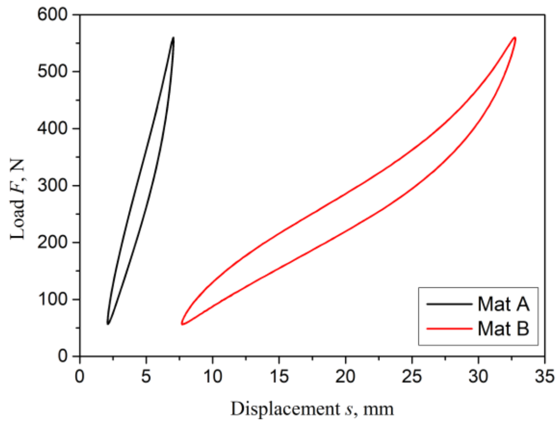

Figure 3 Hysteresis curves of Material A (black) and Material B (red). The data shown were recorded at 10000 cycles in force control with F_{max} = 560 N and R = 0.1, with f = 4 Hz.

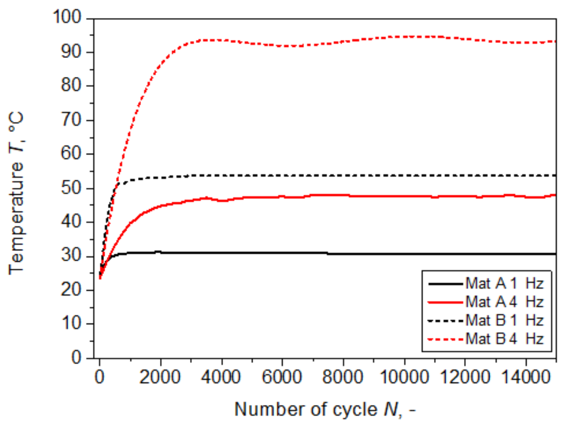

Figure 4 Temperature evolution of 3D dumbbell specimens for material A (black) and Material B (red). The tests were performed in force control with F_{max} = 560 N and R = 0.1, at frequency of 1 (full lines) and 4 Hz (dashed lines).

In Figure 5 and 6 two pictures obtained with IR camera during testing of pure shear specimens of material A are reported. From Figure 5 it is possible to observe that the temperature was symmetrically distributed along the height of the specimen while it became asymmetric when the crack developed towards one of the clamps as show in Figure 6. It is important then to consider the position of the measurement of surface temperature

Table 2. Plateau surface temperature T_S and temperature increase with respect to the specimen in the unload state ΔT for both material using dumbbell geometry. The test were performed in load control using a load ratio R = 0.1 and a maximum force F_{max} = 560 N.

f (Hz)	Material A		Material B	
	T_S (°C)	ΔT (°C)	T_S (°C)	ΔT (°C)
1	31	6	54	29
4	49	24	94	70

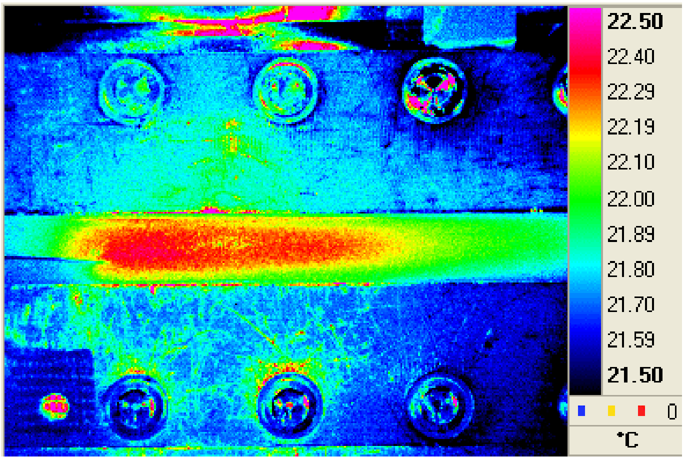

Figure 5 Picture recorded with an IR camera during testing of a pure shear specimen. The temperature is symmetrically distributed along the height of the specimen.

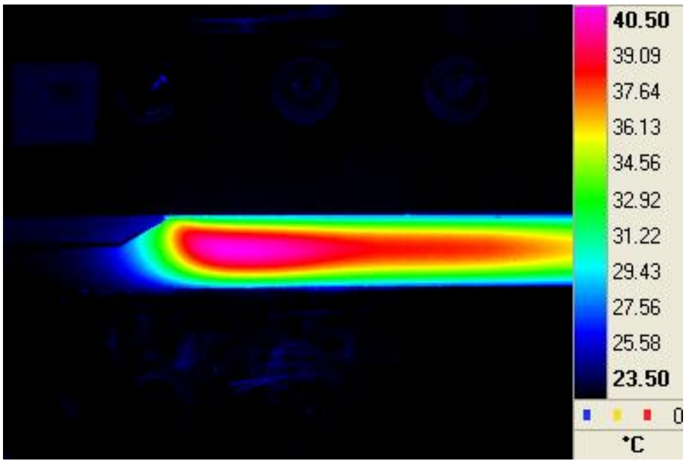

Figure 6 Picture recorded with an IR camera during testing of a pure shear specimen. The temperature is asymmetrically distributed along the height of the specimen due to crack development towards the upper clamp.

3.3 *Temperature profile*

The temperature increases upon loading are evaluated using surface temperature values. However, due to the low thermal conductivity, it is reasonable to believe that the temperature is not homogenous in the thickness. In order to get an idea of the internal temperature distribution, an equation for retrieving the temperature profile along the thickness can be obtained considering the heat equation with a heating source

$$\rho\, C_P \frac{\partial T}{\partial t} - \nabla(\lambda \nabla T) = \dot{q} \quad (1)$$

where ρ is the density, C_P the specific heat, λ the thermal conductivity and $\dot{q}$ is the internal heat generated per unit volume, which is given by

$$\dot{q} = \frac{f \cdot U_{dis}}{V} \quad (2)$$

where U_{dis} is the energy dissipated per cycle, f the frequency and V the volume. In order to get a solution, some assumptions could be done. Considering the equilibrium condition when the temperature show a plateau value, the rate of variation of temperature is zero $\partial T/\partial t = 0$. By considering a rectangular plate (useful for pure shear specimens), it is possible to consider that the temperature is homogenous along the width and the height and that it varies only in the thickness, allowing to simplify the problem to a 1D case. Moreover, it is possible to consider the thermal conductivity constant with temperature; this assumption is justified by the experimental results shown in section 3.1. Taking into account all these considerations, equation (1) can be simplify into

$$\frac{d^2T}{dx^2} = -\frac{\dot{q}}{\lambda} \quad (3)$$

The solution can be retrieved then by considering the following boundary condition: at the surface, the temperature T_S is constant, while the continuity of the function in the center imply that $dT/dx = 0$. The solution of the problem is a parabolic function of the thickness L

$$T = T_S + \frac{\dot{q}}{2\lambda} \cdot \left(\frac{L^2}{4} - x^2\right) \quad (4)$$

In the center, for $x = 0$ the temperature is

$$T = T_S + \frac{\dot{q}L^2}{8\lambda} \quad (5)$$

Similar arguments could be considered for the cylindrical case (useful for dumbbell specimens) of radius R, obtaining

$$T = T_S + \frac{\dot{q}R^2}{4\lambda} \cdot \left(1 - \frac{r^2}{R^2}\right) \quad (6)$$

and in the center, for $r = 0$

$$T = T_S + \frac{\dot{q}R^2}{4\lambda} \quad (7)$$

The treatment above can be found in literature (Holman, 2010). By using this treatment, it was possible to evaluate the temperature distribution along the thickness for both pure shear and 3D dumbbell specimens, by making use of equations 4 and 6 respectively.

In Figure 7 and 8 the calculated temperature profile along the thickness for pure shear for material A and B are reported, respectively. In Figure 9 and 10 the calculated temperature profile along the thickness for dumbbell specimens for material A and B are reported, respectively. The value of surface temperature T_S and the temperature in the center T_C are reported in table 3 and 4.

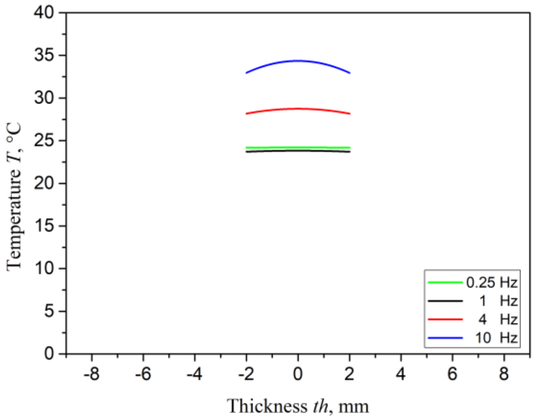

Figure 7 Temperature profile along the thickness of pure shear specimen of Material A. The tests were performed in displacement control with Rε= 0.5 with ε_{max} = 10 % at different frequencies.

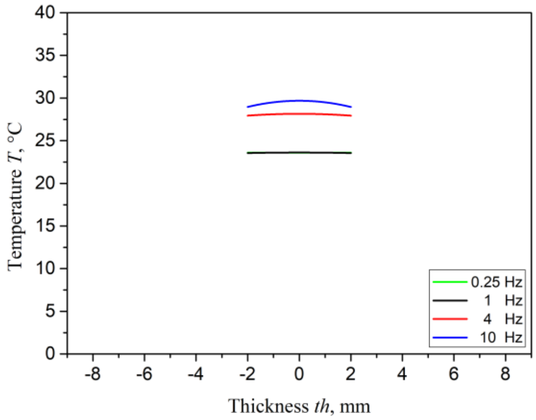

Figure 8 Temperature profile along the thickness of pure shear specimen of Material B. The tests were performed in displacement control with Rε= 0.5 with ε_{max} = 10 % at different frequencies.

Even for pure shear specimens, the surface temperature was higher for higher frequencies for both material, as depicted in Figure 7 and 8 and reported in Table 3. Moreover, it is possible to observe that the temperature is substantially constant along the thickness in all tested conditions. This is related to the low thickness (4 mm) of the specimens: the small path of the heat to surface lead to a fast exchange with the environment, limiting the temperature increase. The data suggest that for pure shear specimens, the temperature can be considered homogenous along the thickness and will be accounted as the surface temperature.

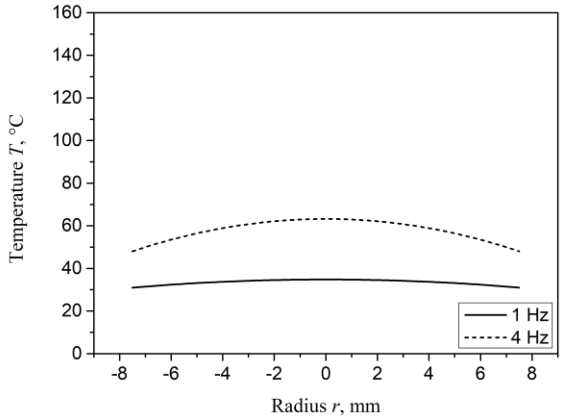

Figure 9 Temperature profile along the thickness of 3D dumbbell specimen of Material A. The tests were performed in force control with F_{max} = 560 N and R = 0.1, at frequency of 1 and 4 Hz.

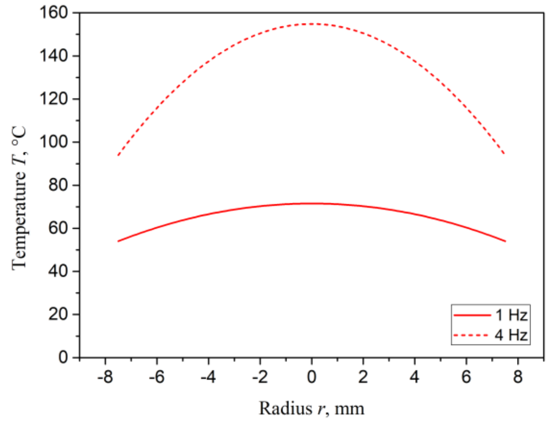

Figure 10 Temperature profile along the thickness of 3D dumbbell specimen of Material A. The tests were performed in force control with F_{max} = 560 N and R = 0.1, at frequency of 1 and 4 Hz.

Table 3. Plateau surface temperature T_S and temperature in the center T_C for pure shear geometry of both material at different frequencies.

f (Hz)	Material A		Material B	
	T_S (°C)	T_C (°C)	T_S (°C)	T_C (°C)
0.25	24	24	24	24
1	24	24	24	24
4	28	29	28	28
10	33	34	29	30

Table 4. Plateau surface temperature T_S and temperature in the center T_C for 3D dumbbell geometry of both material at different frequencies.

f (Hz)	Material A		Material B	
	T_S (°C)	T_C (°C)	T_S (°C)	T_C (°C)
1	31	35	54	62
4	49	73	94	162

As depicted in Figure 9 and 10 and the data reported in Table 4, the higher thickness of 3D dumbbell specimens (15 mm of diameter) leads to much higher temperature increases and very high values in the center of the specimen. For 1 Hz the temperature in the center was higher than the surface one of 4 °C for Material A and 8 °C for Material B. For 4 Hz the temperature in the middle resulted higher in the center of 24 °C for material A and 68 °C for material B. Such temperatures inside the specimen, not only could influence the fatigue properties but they could also lead to thermal failure. When dealing with fatigue testing, for dumbbell specimens it is therefore necessary to try to avoid such temperature increases by using low testing frequency or, when it is not possible, to take into account the temperature evolution especially in the core of the specimen. By doing so, the discrimination between fatigue and thermal failures could be possible.

4 CONCLUSIONS

In order to have more insights of heat build-up during fatigue testing, several tests were performed for two different rubbers. Thermal conductivity of both materials was measured using two techniques along the range of possible utilization of rubber components and it was found that the thermal conductivity was low for both materials and it remained constant along the temperature range. The surface temperature evolution during loading was monitored for 3D dumbbell specimens, revealing that even a small variation of frequency could result in much higher temperature increases. The surface temperature of pure shear specimens was recorded also with an IR camera, revealing that the temperature distribution along the height of the specimens is affected by the position of the crack tip. Moreover, an equation for calculating the temperature profile along the thickness was retrieved from the heat equation and the temperature profiles were calculated for both dumbbell and pure shear specimens. Based on the calculations, the temperature for pure shear specimen could be considered as homogenous in the specimen thickness, while the higher temperatures in the center should be taken into account for 3D dumbbell specimen during fatigue analysis.

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