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HEAT BUILT UP DURING DYNAMIC MECHANICAL ANALYSIS (DMA) TESTING OF RUBBER SPECIMENS

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ABSTRACT

The viscoelastic properties of rubbers play an important role in dynamic applications and are commonly measured and quantified by means of Dynamic Mechanical Analysis (DMA) tests. The rubber properties including the static and dynamic moduli are a function of temperature; and an increase in the temperature leads to a decrease in both moduli of the rubber. Due to the heat generation inside the rubber during the DMA test and the possible change of the rubber properties it is important to quantify the amount of temperature rise in the rubber specimen during the test. In this study, a Finite Element Analysis (FEA) model is used to predict the heat generation and temperature rise during the rubber DMA tests. This model is used to identify the best shape of the specimen to achieve the minimum increase in temperature during the test. The double sandwich shear test and the cyclic compression tests are considered in this study because these two tests are mostly used in industry to predict the rubber viscoelastic properties.

INTRODUCTION

Within the context of tires, wiper blades, conveyor belts, sealing or any kind of elastomer implemented in dynamic applications, the viscoelastic properties of elastomers has remarkable influence on performance, quality and longevity of the part. Materials, such as rubbers, exhibiting both viscous and elastic behaviors as they undergo deformation are called viscoelastic materials. If a material is purely elastic, the phase difference between the stress and strain waves is zero degree; and if the material is purely viscous, the phase difference is 90 degree. A viscoelastic material has a phase difference somewhere between these two extremes [1]. In the stress-strain curve of the viscoelastic material during a full loading cycle, due to the mentioned effect, a hysteretic loop can be seen. From the area of this hysteretic loop, the amount of energy dissipation can be calculated [2, 3]. As an example, thermal conductivity of the Styrene-Butadiene rubber (SBR) is really low compared to the steel KSBR=0.25 W/(mK) [4], Ksteel=51.9 W/(mK) [5]. Due to the low thermal conductivity of rubber, the generated heat causes the temperature increase inside the rubber. This phenomenon is known as heat built-up in rubbers [6]. Another characteristic of viscoelastic materials is time- and temperature-dependency of properties [7, 8]. It means for a given viscoelastic material, the phase difference between the stress and strain waves is a function of the material temperature and the frequency of these waves which in turn affects material properties.

Dynamic Mechanical Analysis (DMA) is a technique to study viscoelastic properties of elastomers in dynamic application. For this aim a stress or strain waive is applied to a viscoelastic material and phase angle and dynamic response is analyzed. From these data, the damping factor, tan δ, can be calculated and the complex modulus and viscosity data can be detected. Basis of DMA technique is to investigate time- and temperature-dependency which is a characteristic of viscoelastic materials. DMAs and these approaches have been studied in several publications [1, 9-13] especially, readers are referred to the papers published by Nolle [11] and Nijenhuis [12]. ASTM standards are also user-friendly sources to use DMA systems [14-20]. DMA devices increase the temperature of rubber and perform the test at low frequencies and then master curves or the Williams, Landel and Ferry (WLF) equation are used [21] to predict the rubber properties at high frequencies. In the endeavor to find rubber properties from this approach, heat built-up is assumed to have negligible effect on properties which might not be reliable. In some rubbers with reinforcing fillers such as carbon black and silica, the effect of filler content [22-26], the crosslinking density, the process parameters [27, 28], the ambient temperature [29] and loading frequency [4] on

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heat build-up have been studied by researchers. Besides, chemical and physical changes of the rubber structure at elevated temperature and operating variables are some other parameters affecting the DMA test results [6, 28, 30], that Hardware In the Loop (HIL) can be a reliable way to simulate them [31, 32].

The DMA shear and compression tests look like a rubber metal sandwich and heat generation in rubber metal block is numerically studied by Finite Element Analysis (FEA) [3, 33, 34] and is experimentally tested [6, 35]. Also it has been proven that heat built up is affected by the rubber geometry, such as with increasing the rubber thickness the path to transfer the heat through the material would be bigger [36].

Therefore, it can be concluded that the uncertainty of DMA tests depends mostly on the temperature increase inside the specimen which might lead to discrepancy of properties at different parts of the test specimen. This will necessitate the need for a satisfactory choice of shape factor which is the main destination of this research. Determining the best shape factor resulting in least possible heat generation during different DMA shear and compression tests is performed with the use of COMSOL Multiphysics software.

RUBBER DYNAMIC RESPONSE

Following equations give the material viscoelastic response to the sinusoidal strain wave [10]:

$$\varepsilon = \varepsilon_0 \sin(wt) \quad (1)$$

$$\sigma = \sigma_0 \sin(wt + \delta) \quad (2)$$

here ε_0 is the maximum amplitude of the strain, The ratio between the loss and storage moduli (E"/ E') gives the mechanical damping factor (tan δ) which is a measure of the amount of deformational energy that is dissipated as heat during each cycle. E' and E" represent the real and imaginary components of this vector thus [10]:

$$E^* = E' + E'' \quad (3)$$

Complex modulus will be used as a means for expressing both the ordinary dynamic elastic modulus and the mechanical loss in the material as a complex number [10].

$$E' = E^* \cos\delta \quad (4)$$

$$E'' = E^* \sin\delta \quad (5)$$

$$\tan\delta = E''/E' \quad (6)$$

The rubber specimen is clamped between two metal parts as shown in Fig. 1. These two metal parts and the clamp are considered as ideal heat sink for the specimens and the maximum temperature reached in the specimen is determined using finite element analysis (FEA). Eq.7 represents the heat generation in the viscoelastic materials as a function of frequency and strain amplitude. For simulation of heat transfer in specimen the COMSOL Multiphysics software is used.

$$\dot{Q} = 4VfE''\varepsilon_0^2 \sin^2(wt) \quad (7)$$

Where V is the specimen volume and f is the frequency.

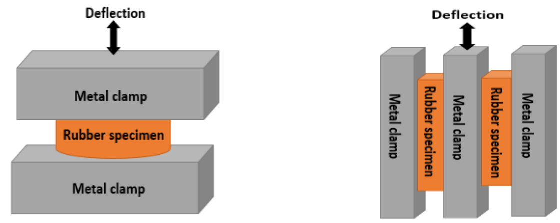

Figure 1. Schematic of the (a) tension-compression and (b) shear DMA tests.

MODELING

Test specimens for compression and shear DMA tests are shown in Fig. 2 and the geometry of these specimens are in Table 2. The reason to have these geometries is due to previous works on literature and recommendations of commercial instrument companies. The rubber block shape factor is defined as loaded area divided by bulge area [4]. For all of the specimen dimensions the shape factor is reported in Table 1. In addition, the clamp is made from stainless steel and the unfilled rubber is used as test specimen material. The dependency of complex shear modulus of unfilled rubber on frequency and temperature is calculated based on the data reported in Ref. [37] and is used as an input MATLAB code for modeling in COMSOL Multiphysics software, that is a suited way to study the heat transfer modeling[38-40].

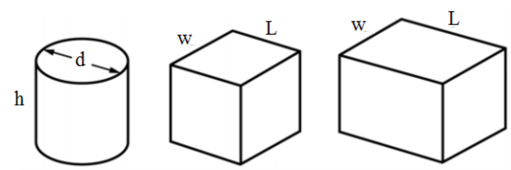

Figure 2. Geometry of test specimen for compression and shear DMA tests

Table 1. Test specimen for DMA tests

Specimen		h (mm)	D (mm)	W (mm)	L (mm)	Shape factor
Square Compression	Size 1	19.5	-	25	25	0.32
	Size 2	10	-	20	20	0.5
Circular Compression	Size 1	12.5	19.5	-	-	0.39
	Size 2	10	10	-	-	0.25
Double shear	Size 1	5	-	40	16	1.14
	Size 2	4	-	10	10	0.62

Three different analyses are done on specimens while temperature of metal plates are kept fixed at each test temperature to recognize the best shape factor for the DMA tests. In the first study for each temperature in the range of -100 to 100C, the frequency sweep (1-80Hz) is applied for 2 minutes soak time and the maximum temperature inside the specimen is calculated. Frequency sweep at different temperatures is the way that commercial DMA's used to calculate the master curves with the use of WLF equation. For modeling at each temperature it is assumed that the specimen is placed in that temperature for a while and the specimen and metal clamps are in that specific temperature in the beginning of the test. In the second study, a change in the compression amplitude known as strain sweep in the range of 1-30% is applied to all specimen geometries in a 2000µm/min displacement rate and 5 minutes soak time and the maximum temperature inside the specimen is calculated. In the third study the effect of specimen thickness and width on maximum temperature inside the rubber is investigated.

MODEL VALIDATION

Luukkonen et al. [36] tested two structural steel layers sandwiching a styrene-butadiene rubber under compression test. The thickness of each steel layer and the SBR layer are 5 mm and 15 mm, respectively. The width and length of all layers are set to be 100 mm thus making an effective area under compression of 10000 mm^2. The compression test runs in dynamic compression of 7.5% and 6 HZ frequency and 18% and 2 HZ frequency, respectively. The test duration is 12 hours. The surface temperature of the intact rubber is measured by the use of thermal camera and thermoelements inside the rubber specimen is used to measure the bulk rubber temperature. For validation, the Ref. [36] geometry and boundary conditions of the compression test is simulated on COMSOL Multiphysics software and is shown in Fig. 3.

Extremely fine mesh is used and the model have 191313 mesh elements. the Ref. [36] results show that after approximately 400 minutes the temperature stabilized therefore to decrease the simulation time, the results are compared for just this time interval.

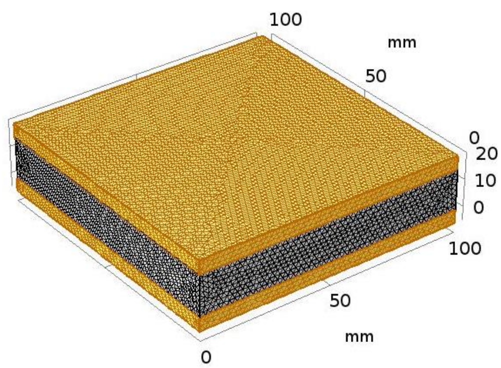

Figure 3. Validation model geometry and finite element mesh.

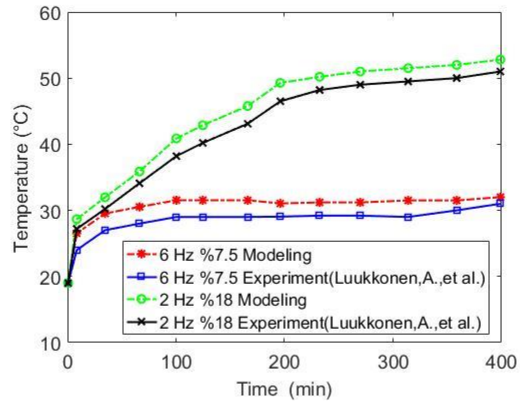

Figure 4. Comparison of the developed model with Luukkonen et al results [36]

Luukkonen et al. [36] test on temperature increase of the bulk rubber after 700 minutes of compression test is compared with modified model and a comprehensive agreement is seen between reference data and the model output voltage in Fig 4. The maximum precision uncertainty is 7% occurred on 6Hz and 18% compression at 207 min. The main reason for this difference is the assumption of keeping the metal clamp at the fixed temperature in COMSOL Multiphysics software modeling but this temperature increase practically is conducted to metal layer thus increasing metal temperature or is consume to the structural changes of rubber such as plastic deformation.

RESULTS AND DISCUSSION

The Circular and Square shape specimen for compression test and Double shear specimen with given geometry in Table.1 are modeled in COMSOL 5.3. Extremely fine mesh is used for all the geometries and the number of mesh elements is presented in Table 2.

Table 2. Number of mesh elements

Circular Compression		Square Compression		Double shear	
1	2	1	2	1	2
50506	79957	198791	311129	20855	39461

The temperature changes during frequency sweep (1-80 Hz) of compression test with 10% dynamic compression, for different temperatures, while temperature of metal plates are kept fixed at each test temperature, is calculated for two specimens of square shape is shown in Fig. 5 and Fig. 6 respectively. The thermal conductivity of the metal clamp is high thus the assumption of keeping the metal clamp temperature fixed at each test temperature can be fulfilled. As it is obvious by an increase in frequency the maximum temperature inside the specimen increases. In addition, as the specimen volume increases the maximum temperature increases as a result. It is reported that as soon as the inner part of the rubber reaches about 200°C the blowout occurs [4] thus for the both square compression specimen sizes with given geometries in Table 1 the test with the 80 Hz frequency at 100^{o} C, brings the rubber inner temperature more than 155^{o}C and the results of that test cannot be reliable.

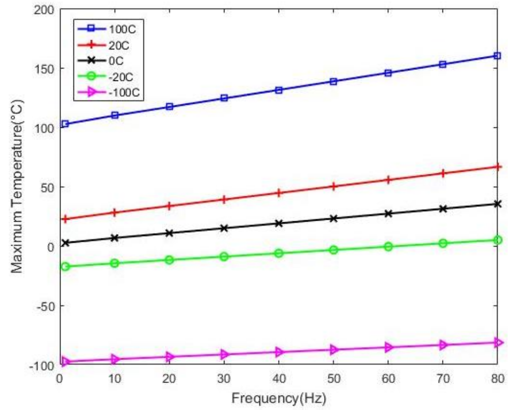

Figure 5. Maximum Temperature of frequency sweep (1-80Hz) of compression test with 10% dynamic compression for Square Compression specimen 1

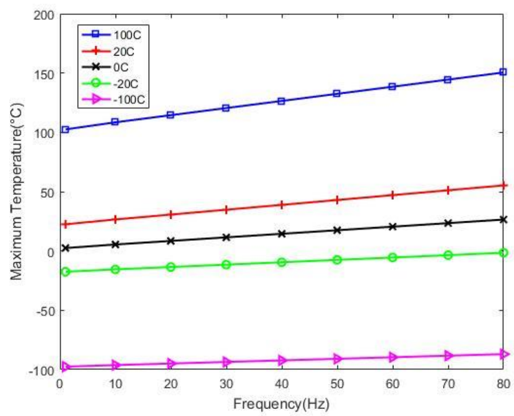

Figure 6. Maximum temperature of frequency sweep (1-80Hz) of compression test with 10% dynamic compression for Square Compression specimen 2

The same frequency sweep test for different temperatures is done on other specimen shapes as Fig. 1 and 2 and the temperature increase in each test specimen is presented in Table3. For all specimen shape factor the temperature increase is not negligible in the frequency sweep test and definitely affect the DMA final results. Specially running the DMA test in high frequency and high temperature is not recommended.

The strain sweep for all the specimen sizes is shown in Fig. 7. Strain change of 0.05% to 25% while the frequency is 10Hz is applied to the specimens over an hour and all the tests are conducted at room temperature (20^{o} C) and the metal clamp temperature is also kept fix at 20^{o}C. By comparing Fig. 5 and 6 with this figure, it can be concluded that dynamic strain change has lower effect on the maximum temperature inside the specimen than frequency changes. Double shear specimen 1 has the lowest maximum temperature although it is 8 times bigger in volume than double shear specimen 2, but it has larger area in contact with metal clamp at 20^{o} C. Consequently, specimens having more area in contact with metal clamp are better for running the DMA tests considering heat buildup inside the specimens. Since the metal clamp conductivity is 200 times greater than the rubber conductivity, the clamp conductivity effect on the temperature distribution in the rubber specimen is assumed negligible

Table 3. Temperature increase for each test temperature in frequency sweep test

Test temperature (^{o}C)		100	20	0	-20	-100
Specimen temperature increase (^{o}C)	Square compression size 1	57.6	40	32.8	22.4	16.1
	Square compression size 2	48	32.8	24	16	10.5
	Circular compression size 1	54	37.3	29.2	20	14
	Circular compression size 2	62.3	51.2	44	35	22.7
	Double shear size 1	28	20	16	13.6	8
	Double shear size 2	36	32	25.6	21.6	16

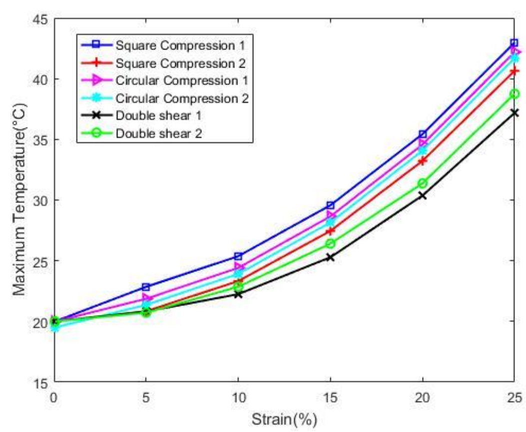

Figure 7. The change of maximum temperature with strain at 10Hz frequency

In another study the effect of specimen thickness on the heat buildup is reviewed for the square compression shape 1. At 20C and 10% dynamic compression the thickness is decreased from 19.5 to 5 mm and the result is shown in Fig. 8. By decreasing the thickness, the internal maximum temperature is increased. While the effect of temperature increase on the DMA results might be considered as a drawback, it is better to use the thicker sample for the DMA test.

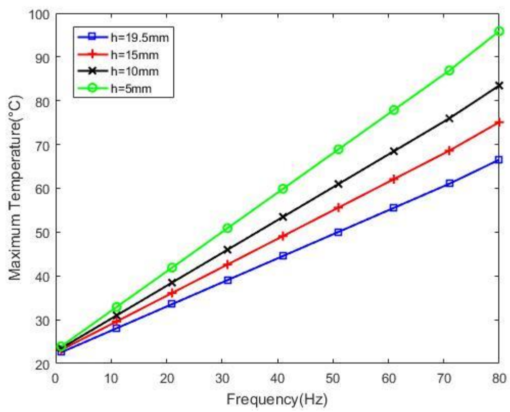

Figure 8. The effect of the specimen thickness on the maximum rubber temperature in frequency sweep compression test

Fig. 9 shows the effect of width increase on the maximum temperature inside the rubber. The square compression shape 1 width, at 20°C, 10% strain and 10Hz, is changed from 10 to 30mm. The temperature increase seen is just 0.12 °C with such a substantial width increase. According to Fig. 8 at 20°C and 10% compression, by 14.5 mm increasing the thickness, the temperature changes will be 5°C at 10Hz. As mentioned before, by extending the width the thermal conduction area with the metal clamp is enlarged, therefore increase in the specimen contact surface with the metal clamp has positive effect accordingly.

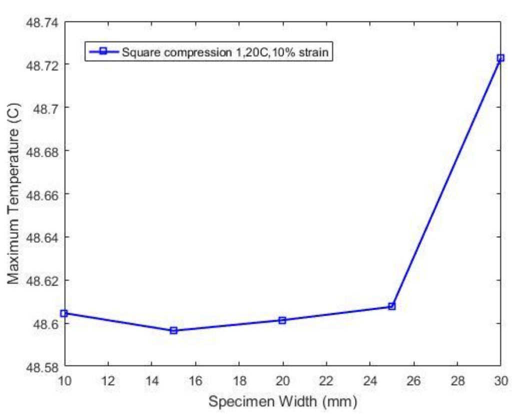

Figure 9. The effect of the specimen width on the maximum rubber temperature in frequency sweep compression test at 10% strain and 10Hz frequency

The specimens shape factor is presented in table 1 and based on the double shear 1, is the most excellent one with which minimum heat generation can be achieved. For compression test the square 2 shape with 0.5 shape factor is the most outstanding one among the ones covered in this study. In addition it is proven that bigger shape factor is lead to reliable DMA test results regarding to heat buildup. It is more reasonable to use materials with high thermal conductivity for clamps in DMA tests and run the test in low temperatures.

CONCLUSION

Rubber as a viscoelastic material has mechanical properties that are time and temperature dependent such as complex modulus. Complex modulus is a function of the material temperature and frequency. Complex modulus is measured with DMA tests thus better understanding of the heat generation in rubber is necessary to have reliable test results. In this paper the maximum temperature inside the rubber was calculated in compression and shear DMA tests using development of an FEA modeling in COMSOL Multiphysics software. It is concluded that by an increase in frequency and strain the maximum temperature inside the specimen increases. The increase in the specimen thickness leads to a decrease of the maximum temperature inside the rubber. And bigger are in conduction with the metal clamp is better to have smaller temperature change during the DMA test. In addition, without any further consideration to decrease the rubber temperature, running the test with 10% compression for above 70 Hz is hard to conduct and rubber specimen will reach the blowout temperature undesirably. For all DMA tests it is recommended to select materials with high thermal conductivity for metal clamp and run the test in lower temperatures. The best shape factor is 1.14 for shear test and 0.39 for compression test and is chosen according to common specimen dimensions on commercial DMA's.

ACKNOWLEDGMENTS

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NOMENCLATURE

σ	Stress
σ 0	Initial Stress
ε	Strain
ε0	Initial strain
δ	Phase angle
f	Frequency
F	Force
E'	Storage modulus
E"	Loss modulus
E*	Complex modulus
$\dot{Q}$	Rate of heat generation
tan δ	Damping factor
t	Time
V	Volume
σ	Stress

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