

On the Gough-Joule Effect of Rubber

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Abstract

For the demonstrational experiment on rubber elasticity, heat effect of deformed (stretching and retracting) rubber is quantitatively measured. Quantitative data could be obtained by use of a thermocouple equipped in a simple tension apparatus. It is thought that the method is suited for the demonstration, since it is easy, simple and inexpensive.

1. Introduction

In teaching course of polymer science, emphasis of explanation on rubber elasticity is needed since it leads to a general concept of the variety of conformation of macromolecules.

It would be helpful to the teaching purpose if we can use a experimental demonstration on rubber elasticity for individual students along the lecture concerned. Probably one of the most simple, inexpensive and effective experiment on the elasticity is sensory observation of temperature changes, *i.e.*, stretching a piece of rubber quickly and after that touching it to one's lips shows somewhat warmer and quickly retracted the rubber somewhat cooler. Although such practice is very easy to perform for all students, more quantitative data of the temperature changes would be necessary for their more precise understanding.

In 1942 Dart et al.¹⁾ reported the temperature changes of stretched and retracted rubbers with use of the single extension apparatus coupled with a thermocouple. Their method would be satisfactory for demonstration.

In the following a description of the test of simple inexpensive experiment based on the Gough-Joule effect on rubber elasticity aimed for student's experimental demonstration is given. Basically the method is followed that of Dart et al.¹⁾

2. Rubber elasticity—Gough-Joule effect²⁾

Consider a piece of rubber band or string of length l which is stretched in dl by external force K under isothermal condition at temperature T . From the thermodynamic laws K reads

$$K = \left(\frac{\partial U}{\partial l} \right)_T - T \left(\frac{\partial S}{\partial l} \right)_T \quad (1)$$

since, in rubber, there is no volume change upon stretching. In eq (1) U is the internal energy and S is the entropy of the rubber. From Meyer and Ferrie's experiment it has been shown

that in rubber $\left(\frac{\partial U}{\partial l}\right)_T$ is smaller than $\left(\frac{\partial S}{\partial l}\right)_T$, and is often neglected as 0. Then in rubber stretching

$$K = -T\left(\frac{\partial S}{\partial l}\right)_T \quad (2)$$

and

$$\left(\frac{\partial S}{\partial l}\right)_T < 0 \quad (3)$$

since both K and T are positive. Equation (3) means in the stretched rubber decreasing entropy evolves heat, and *vice versa*. It also means the rubber is contracted upon warming and *vice versa*. These phenomena are known as the Gough-Joule effect. Starting from eq (1) quantitative expression for temperature change ΔT and elongation Δl of stretched rubber is given in eq (4)

$$\Delta T = -\frac{T}{C_e}\left(\frac{\partial S}{\partial l}\right)_T \Delta l \quad (4)$$

where C_e is heat capacity of the rubber. This shows ΔT is approximately proportional to Δl . Eq (4) is a quantitative expression of the Gough-Joule effect.

3. Experimental

Rubber sample used was commercial vulcanized rubber string for model airplane with a cross-sectional size $3.2 \text{ mm} \times 1 \text{ mm}$. The appearance was dark brown and the colour indicated that the rubber is unloaded natural rubber. This was also estimated from the stress-strain curve.

The extension apparatus with the thermocouple arrangement is shown in Fig. 1 (a) and (b). The both ends of the rubber were tightened to the movable arm so that the stretching ratio of the sample could be regulated by the position of the arm. Stretching of the rubber was done rapidly by moving of the arm by hand along the stay. A thermocouple of chromel and alumel wire 0.13 mm in diameter was used for reading the temperature changes of the rubber sample. The size of the junction of the wire was small enough for reading small temperature changes. The reading of the thermocouple responses was recorded on a digital panelmeter having sensitivity of 0.001 mV and fast data sampling time of 4 per second.

To obtain the temperature changes of the sample correctly, trial was made as to the position of the thermocouple in relation to the rubber. At first we thought the position would be enough just as the focus of the refractive surface of the dome which is positioned quite near, but apart, from the rubber sample's surface as is shown in Fig. 1(a). The dome was made of polystyrene foam having inner surface with aluminum coating. This arrangement is to catch the heat emission from the stretched rubber by the thermocouple without any friction between the thermocouple and the rubber sample. In this case, however, none of the

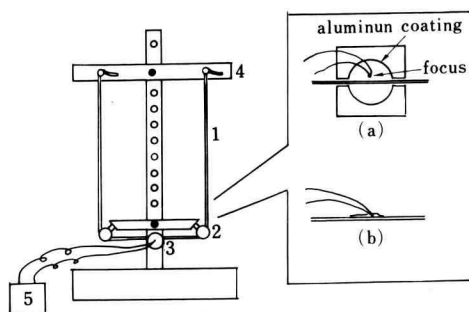


Fig. 1. Experimental apparatus.

1. rubber band 2. pulley 3. thermocouple 4. movable arm 5. digital panel meter

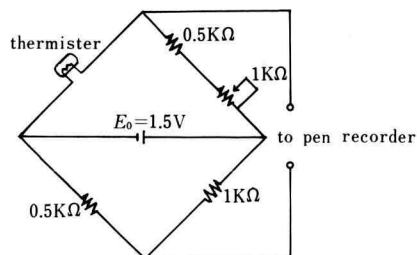


Fig. 2. Thermister-bridge.

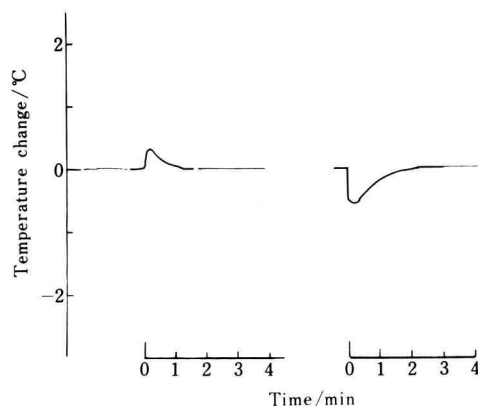
thermocouple response was obtained.

Second trial was the thermocouple positioned directly onto the sample's surface and tightly fixed it to the position with small cellotape (Fig. 1(b)). In this method the thermocouple responses were very quick with good duplicacy. Then this method was used throughout all the measurements.

For more precise temperature determination the thermister-bridge shown in Fig. 2 was used. This bridge has three advantages; has high sensitivity for temperature change of 0.001°C , can drive a chart-recorder directly and quite inexpensive.

4. Results

In Fig. 3 and 4, the temperature changes of the rubber at lowest and highest stretching ratios are shown. The sharp temperature changes can be seen on the curves immediately after on stretching and on retracting. Generally reproducibility of the curves is good with the suggestion that the endothermic and exothermic processes are reproducible. The peak

Fig. 3. Temperature change of the sample after stretching or releasing, $\lambda = 2.45$.

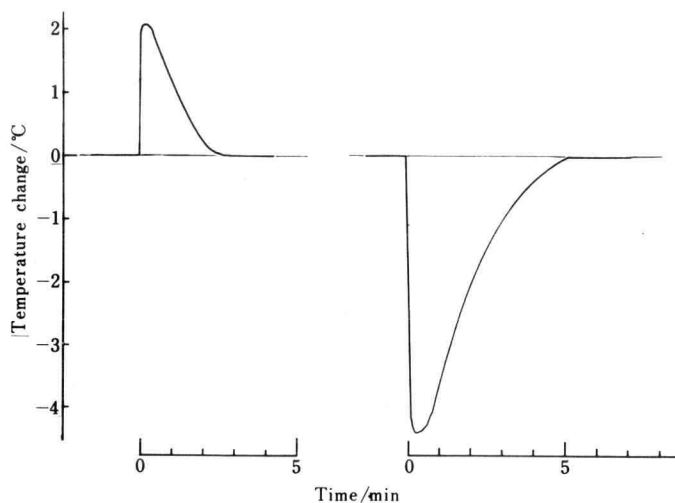


Fig. 4. Temperature change of the sample after stretching or releasing, $\lambda = 5.12$.

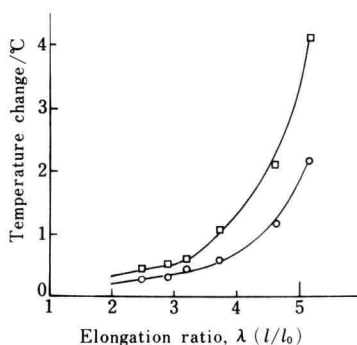


Fig. 5. Peak temperature change vs elongation, λ
 ○: stretching, □: releasing.

of the curve gives temperature change ΔT while the area under the curve give enthalpy change ΔH . Both ΔT and ΔH are larger when the deformation ratio is higher. When highest stretching the extension curve is definitely lower than the retraction curve. The reason is unambiguous, but one reason which might be considered is the volume ratio between the thermocouple junction and the rubber part where the heat flow occurs to the junction. When stretching the volume ratio is getting smaller compared to that of retracting. This situation will be confirmed using more broader sample size.

From eq (4) it is predicted that temperature change ΔT is proportional to stretching ratio λ . Fig. 5 shows a plot of ΔT against λ . Up to $\lambda=3$ approximately linear relation is obtained. It is noticed that λ at much higher region a large upswing of the curve is clear. This upswing may be attributed to the crystallization due to high stretching. Dart et al.¹⁾ pointed out the heat effect by crystallization on the extension curve with time lag of response

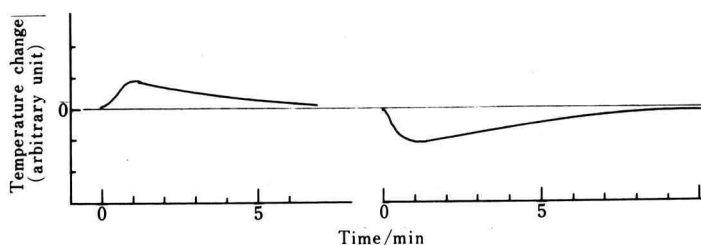


Fig. 6. Temperature change of water.

of the thermocouple. Pines and others²⁾ also suggested the bigger heat evolution due to the crystallization than the entropy heat effect we are now concerned. In our experiment no such time lag response was seen. As to the crystallization effect on the heat evolution, much experimental work are necessary by use of non-crystallized rubber such as synthetic styrene-butadiene rubber.

The heat effect is also confirmed by next method. A trial for calorimetric measurement of the heat exchange when the rubber sample is deformed isothermally, *i.e.*, stretching and retraction of the rubber part between the two pulleys in Fig. 1 in 4-5 ml water surrounded by good thermal insulator, was made. The temperature changes of the water recorded by the thermister-bridge immersed in the water are shown in Fig. 6. It is clearly seen in this figure that the sharp temperature change is bigger in retraction than in stretching. This is probably due to the rubber volume change immersed in the water.

5. Conclusion

Experimental results obtained show that an experimental demonstration concerning rubber elasticity can be performed quite easily. The simple and inexpensive way is specially adapted to a practice of each individual student.

During in this experiment, we noticed that much experimental data are needed for various rubbers and related materials.

Apart from the purpose of demonstration, determination of the temperature changes in more vigorous way, *i.e.*, measurement *in vacuo*, or calorimetric measurement is much interest in understanding of rubber elasticity.

Addendum

As mentioned before another type of experiment of the Gough-Joule effect is contracted of rubber when heating. Applying the contraction, thermally rotating wheel can be constructed by employing rubber as the working material³⁾. The wheel is also constructed in our laboratory. The structure is shown in Fig. 7. Although the wheel could rotate by warming, continuous rotation was hardly attained. In order to obtain smooth rotation it is stressed that use of good wheel balance, light wheel weight, frictionless bearing, and

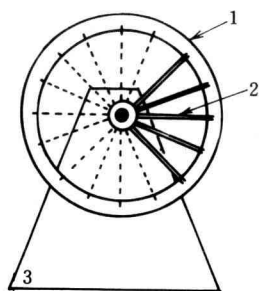


Fig. 7. Thermally rotating wheel.
The rubber bands are heated by electric hot plate or ir lamp.

1. wheel (veneer plastic combination : 24 cm in diameter)
2. rubber band
3. stand

moderate tension of the rubber spokes are critical.

In our case only very slow discontinuous rotation was obtained. Therefore demonstration of this type may be not recommended.

Acknowledgement

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