Journal of Macromolecular Science, Part A
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713597274

Electrothermomechanical Film. Part I. Design and Characteristics

A. Savolainen[a]; K. Kirjavainen[a]
[a] Institute of Plastics Technology Tampere University of Technology, Tampere, Finland

To cite this Article Savolainen, A. and Kirjavainen, K.(1989) 'Electrothermomechanical Film. Part I. Design and Characteristics', Journal of Macromolecular Science, Part A, 26: 2, 583 — 591
To link to this Article: DOI: 10.1080/00222338908051994
URL: http://dx.doi.org/10.1080/00222338908051994

J. MACROMOL. SCI.–CHEM., A26(2 & 3), pp. 583-591 (1989)

ELECTROTHERMOMECHANICAL FILM. PART I. DESIGN AND CHARACTERISTICS

A. SAVOLAINEN* and K. KIRJAVAINEN

Institute of Plastics Technology
Tampere University of Technology
SF-3310 Tampere, Finland

ABSTRACT

Electrothermomechanical film (ETMF) is a cellular, biaxially oriented plastic film which is coated with electrically conductive layers. It is an elastic impedance. ETMF relates electrical, mechanical, and thermal energies as well as parameters. The functional basis of the film comprises the compression of gases, the mechanical parameters of the film, and the electric or magnetic field. By exploiting these basic characteristics, the film can be used in measuring techniques, in acoustics, in ultrasonics, in motion elements, in energy transformation, etc.

INTRODUCTION

The object of the present paper is to provide a dielectric and elastic film (ETMF) [1] with which different kinds of electrothermomechanical devices can be realized. If the electrostatic and electromagnetic forces across an elastic film are to be high, it is essential that the film layers are as thin as possible [2]. The electrostatic and electromagnetic forces are inversely proportional to the second power of the distances between the electrodes. On the other hand, the breakdown voltage of both the plastic films and the gas bubbles in them increases as the distances decrease, according to Paschen's law [3,4].

It is possible to produce small, low-thickness gas bubbles and thin elastic material by orienting the foamed film in both the longitudinal and transversal directions, so that the bubbles assume the shape of flat disks. A dielectric film of this type is therefore a homogeneous film layer foamed to be of the closed-type and oriented by bidirectional stretching and at least partly coated on one or both sides with an electrically conductive layer.

The thickness of films of this type is, e.g., 10 μm, and their field strength is 100 MV/m. Quantities like force (F), pressure (P), surface area (A), thickness of the film (s), electric field strength (E), voltage (U), and dielectrical constants (ϵ), can be related by the following equations:

$$F = pA = (\epsilon E^2 A)/2 = (\epsilon U^2 A)/2s^2. \tag{1}$$

When the film is connected as part of an electric measuring circuit, it is possible to observe a great variety of relationships between the different variables. One thus obtains, with a 10-μm film layer, a force of 100 kN/m^2 with a voltage of 1 kV. By stacking several film layers, the thickness variation can be increased.

Since a multilayer folded structure is capacitative as well as inductive (see Fig. 1), power can be supplied to the structure at a maximal possible speed and with minimal power losses. By manufacturing the film, e.g., of polypropylene,

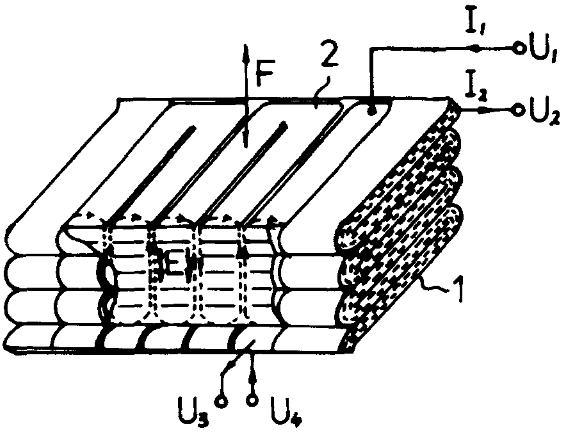

FIG. 1. Multilayer structure of ETMF, which is capacitive and inductive. 1: Individual foamed film matrix. 2: Patterned metal layer through the folded film element to form an electromagnetic circuit.

good mechanical and electrical properties are achieved. The modulus of elasticity of the film can be regulated by regulating the size, shape, and number of bubbles. A film of this kind may be used as a motion element and a vibration surface over a wide frequency range.

MANUFACTURING OF THE ETMF

Figure 2 shows schematically a procedure for manufacturing the film by a two-step continuous process.

First Step

Film-grade polypropylene is extruded as a tube with a wall thickness of about 400 μm, in which round gas bubbles of about 10 μm diameter are formed with 10 μm spacing.

In order to prepare a totally homogeneous extruded tube, we have developed an extrusion head with inner rotating disks [5]. The rotating disks destroy the thermal history of the melt and therefore the bubbles are uniformly distributed in the polymer matrix.

The forming properties of the plastics improve with increasing degree of crystallization, and for this reason the extruded plastic is heat treated in a manner that promotes crystallization, in the present instance, by allowing the plastic to cool down on a cooling mandrel.

The foaming of the plastic can be accomplished in two different ways. In chemical foaming, a foaming agent is admixed with the plastic which, on being heated forms, e.g., nitrogen bubbles. In the injection technique, gas is pumped into the plastic in the extruder and it expands to bubbles when the pressure drops on leaving the extruder.

Second Step

The second step starts with heating the tube in an oven, after which the tube is biaxially oriented by drawing it transversally about 5 times and longitudinally about 8 times to the desired wall thickness. The air or gas for blowing is introduced by the nozzle, its supply pressure being allowed to inflate the heated tube. The bubbles, which have been flattened during the expansion, are now about 0.25 μm high, about 80 μm long, and about 50 μm wide. The added theoretical breakdown strength of the blisters is on the order of 1600 V, and that of the matrix material is about 2500 V. It follows that 1000 V dc/ac strength can be achieved in a 10-μm film.

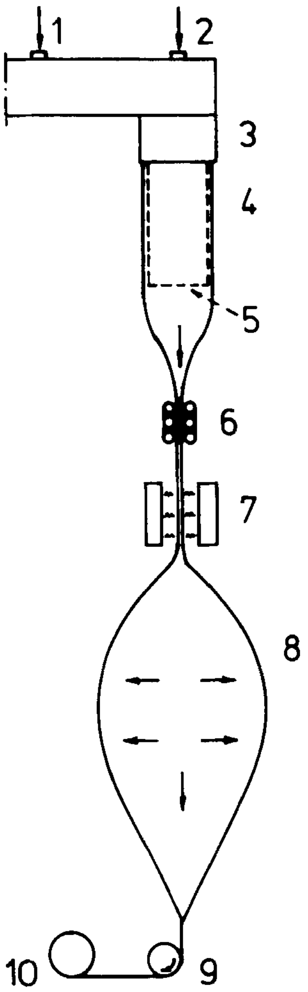

FIG. 2. Biaxial orientation of PP schematically. Extruder (1), air feed (2), die (3), tube (4), cooling mandrel (5), caterpillar (6), heating (7), bubble formation (8), nip roll (9), reel (10).

Finally, the film is wound on a reel to be coated with a conductive layer by vacuum vaporizing, sputtering, or mechanically.

In recent experiments we produced film with an output of 10 m^2/min. The foaming degree was 30%. In order to get a fully conductive layer on both surfaces of the film, the sputtering method was used with copper or aluminum. The metal layers were between 20 and 30 nm thick.

APPLICATION MODES OF THE ETMF

1. Capacitive Transducer

The total capacitance of the ETMF is given by Eq. (2), and the variables changing the capacitance are shown in Fig. 3.

$$C = \frac{A\epsilon_0\epsilon_1}{n(\epsilon_1 s_0 + \epsilon_0 s_1)}, \qquad (2)$$

where A is the film area; ϵ_0 and ϵ_1 are the dielectric constants; s_0 and s_1 are the thicknesses of the gas blisters and the solid plastic, respectively; and n is the number of individual bubble layers. When $\epsilon_1 >> \epsilon_0$, the capacitance changes linearly with pressure.

A capacitance change as a function of temperature of 0.2%/10°C can be

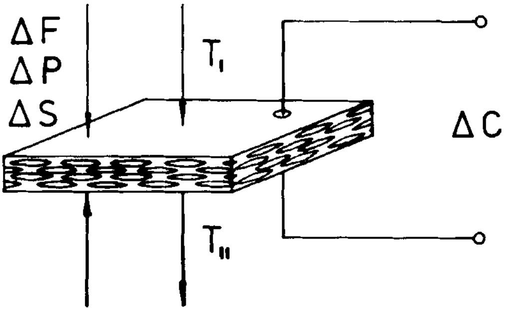

FIG. 3. Capacitance change as function of Δp, ΔF (change in external force), and ΔT (T_1 - T_{11}), i.e., a temperature gradient in which $T_1 \leqslant T_2$ or vice versa.

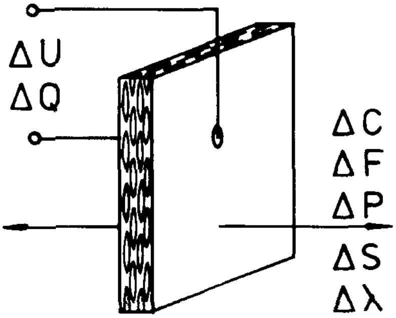

FIG. 4. Electrostatic pressure as a function of electrical charge. ΔQ is a change in electrical charge and $\Delta\lambda$ in heat conductivity.

realized for 30% foaming. In a recent study we reached an estimated level of about 1%/10°C in capacitance change for 50-55% foaming.

The capacitance changes with force and pressure at 10%/atm for 30% foaming and 25%/atm for 50% foaming. Compared with piezoelectric PVDF film, the sensitivity of ETMF is superior and, in addition, the signal of ETMF starts at zero frequency. The sensitivity of the capacitance change in ETMF decreases on repeated bending-compression-stretching.

2. Electrostatic Transducer

A voltage across the film results in a force between the film surfaces (Eq. 1) and a change in the film thickness, so that the force and the internal pressure in film are in balance (Fig. 4). A fundamental equation for electrostatic pressure is

$$p = \frac{1}{2} \epsilon \frac{U^2}{s^2} \tag{3}$$

where U is the voltage and s is the thickness of the film. When trying to reach a 25% decrease in film thickness in a 50% foamed film, a voltage of about 100 V/μm is required. This high voltage indicates that conditions for manufacturing ETMF must be very clean, as is usual in condenser film manufacture.

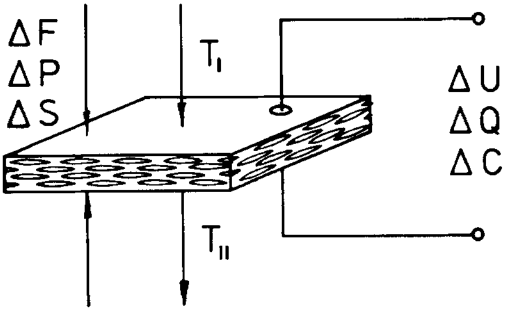

FIG. 5. Polarized ETMF device. Electrical charge as a function of external force.

3. Polarized Generator

An ETMF can be polarized constantly to form an electret. It generates an electric charge which is proportional to the variation of film thickness. The operation is visualized schematically in Fig. 5.

The electret means that, in a strong electrical field, the matrix acquires a permanent electrical charge that is opposite on both sides of each individual lenslike bubble, i.e., the electret characteristic holds throughout the film. This operation mode is analogous to that of single-film electret generators which are used as microphones. Depending on the plastic material, the permanent dipole polarization, i.e., the electret, reaches values of 0.01-0.1 C/m^2 [6, 7].

4. Parametric Generator

The ETMF represents a resonance circuit with inductance L, Fig. 6. By changing C, i.e., by pumping the thickness of the film with a double frequency compared to that of resonance frequency, the mechanical energy is transformed to electrical energy. The amount of transformed energy is [8]

$$W = \frac{1}{2} \Delta C U_0{}^2, \tag{4}$$

where U_0 is a voltage and ΔC is a change in capacitance.

To understand the mechanism of ETMS energy transfer in parametric amplification, it is convenient to think of the ETMF (in Fig. 6) as an elastic

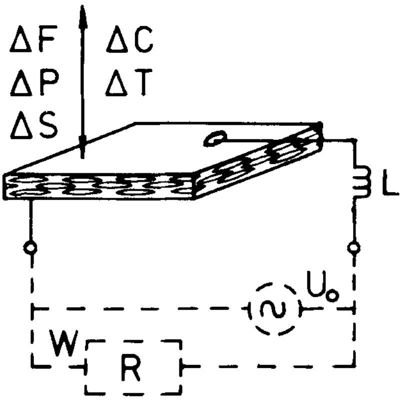

FIG. 6. ETMF as an elastic condenser in a resonance circuit.

capacitor (corresponding to a capacitor with movable plates) which is connected to an inductance and a sinusoidal ac voltage source. At the instant t_1, when the voltage is at a maximum and the gas blisters are pushed by an external force (i.e., pressure), the ETMF capacitor is suddenly released. No mechanical or thermal work has to be done. On the other hand, the gas in the blisters does work when it volatilizes. After release, the ETMF matrix capacitance C is decreased, but the charge Q is unchanged if the release time is very short compared to the natural period of the resonant circuit. Since

$$U = Q/C, \tag{5}$$

the voltage must increase instantaneously. This increased voltage across the ETMF capacitor continues its cycle and returns to zero at time t_2. At this instant the ETMF is compressed by an external force. The work that must be done corresponds to the force of gas compression. If the ETMF matrix is repeatedly released at the times of maximum voltage and pushed together at the times of zero voltage, the voltage will increase until the energy dissipated per cycle by the circuit resistance equals the mechanical energy supplied per cycle. Thus the addition of mechanical energy (work) by pumping the ETMF capacitor at twice the frequency leads to an increase in electrical energy. The inductance can also be varied independently, or capacitance and inductance can be changed together in ETMF devices.

REFERENCES

[1] K. Kirjavainen, U.S. Patent 4,654,546, Electrothermomechanical film and procedure manufacturing same.

[2] H. L. Saums and W. W. Pendleton, *Materials for Electrical Insulating and Dielectric Functions,* Hayden, New Jersey, 1973.

[3] F. Paschen, *Ann. Phys., 37,* 69 (1889).

[4] H. C. Hall and R. M. Russek, "Discharge Inception and Extension in Dielectric Voids," *Proc. IEE, 101*(2), 47-55 (1984) (Paper No. 1618).

[5] A. Savolainen, J. Suomi, and K. Kirjavainen, Patent Application in Europe, the United States, and Japan.

[6] T. Yagi, Y. Higashihata, K. Fukuyama, and J. Sake, *Ferroelectrics, 57,* 327 (1984).

[7] J. X. Wen, *Jpn. J. Appl. Phys., 23,* 1434 (1984).

[8] H. Wetzel and H. Tribursch, *Sol. Energy, 37,* 65 (1986).