Sensors and Actuators A 164 (2010) 46–57

Contents lists available at ScienceDirect

Sensors and Actuators A: Physical

journal homepage: www.elsevier.com/locate/sna

Quantum tunnelling composites: Characterisation and modelling to promote their applications as sensors

Andrés Díaz Lantada*, Pilar Lafont, José Luis Muñoz Sanz,
Juan Manuel Munoz-Guijosa, Javier Echavarri Otero

Grupo de Investigación en Ingeniería de Máquinas – E.T.S.I. Industriales Universidad Politécnica de Madrid, c/José Gutiérrez Abascal, n° 2, 28006 Madrid, Spain

ARTICLE INFO

Article history:
Received 22 March 2010
Received in revised form 9 August 2010
Accepted 2 September 2010
Available online 16 September 2010

Keywords:
Quantum tunnelling composites
Metal–polymer composites
Conductive polymers
Pressure sensors
Behaviour model
Active or “intelligent” materials

ABSTRACT

Quantum tunnelling composites, or “QTCs”, are composites with an elastomeric polymer matrix and filled with metal particles (usually nickel). In a state of rest, these metal particles are not in contact and the polymers act as an insulator, but when the material is suitably deformed, the particles come together (without actually touching) and the electrons can “leap” from the irregularities of some particles to the irregularities of others without any need for contact due to the “quantum tunnel” effect, which causes the electrical resistance to fall drastically.

This paper contains a detailed description of the constituent equation for modelling the behaviour of these materials. It is based on the use of a simple quantum model of a particle breaking through a potential barrier, to which are added effects such as the influence of polymer matrix viscoelasticity on sensor response, the influence of pressure and temperature on the elasticity modulus and the dynamic viscosity of the material, as well as phenomena associated with thermal expansion.

By performing tests under different pressures and temperatures encompassing a wide range of operating conditions for these materials, the constituent equation in question is adjusted and an analysis is made of the goodness of the model proposed. The results of these tests have also enabled certain previously described phenomena to be described in greater detail regarding the in-service response of QTCs when faced with changes in pressure and temperature.

1. Introduction

Quantum tunnelling composites, or “QTCs”, are polymer matrix composites (elastomeric) filled with metal particles and were discovered by the scientist David Lussey in 1997, when he was trying to develop an electrically conductive adhesive. The surprising properties of this new material led to the founding of Peratech Ltd., a company dedicated to research work, the search for applications, and technology transfer involving these materials.

The working principle behind QTCs differs from that of other conductor polymers obtained through percolation (using metal particles, carbon nanotubes, smoke-black and other fillings), which attempt to bring into contact the filled metal particles to obtain electrical conductivity or, at least, considerably reduce the electrical resistance of the polymer matrix [1,2]. However, QTCs, usually obtained by integrating Ni particles of around 100–500 nm into an elastomeric matrix, act differently. In a state of rest, these metal particles are not in contact and the polymer acts as an insulator, but when the material is suitably deformed, the particles come together (without actually touching) and the material becomes an excellent conductor (electrical resistance is reduced by several orders of magnitude).

An explanation for this behaviour was contributed by researchers from Durham University ([3,4]). Since the Ni particles embedded in the polymer matrix have an irregular surface (spiky), when the material is pressed the particles come together and the electrons can “leap” from the irregularities of some particles to the irregularities of others without any need for contact due to the “quantum tunnel” effect (overcoming the non-conductor portion of the polymer between particles).

The more the material is deformed, the greater the reduction in electrical resistance, which is why the use of elastomeric matrices is particularly effective, although for applications that must withstand higher pressures, thermoplastic or thermostable materials can be used.

One of the major advantages of these materials is that since they are insulators when in a state of rest, the electronics fitted to these devices do not consume any energy unless pressure is applied. This helps minimise the size of the feed system required, which boosts multi-purpose usage, particularly that related to the development of implantable medical devices [5] and aeronautic devices Shadow Robot Company [22], where end size is a determining factor.

---

* Corresponding author. Tel.: +34 913364217.
E-mail address: adiaz@etsii.upm.es (A.D. Lantada).

0924-4247/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.sna.2010.09.002

They are also very cheap and easy to obtain, being distributed by various companies at very affordable prices (less than 1 € per sensor), which means that the end applications will not exceed the cost of other solutions available on the market. In fact, apart from Peratech Ltd., various other companies have emerged in the field, such as QIO Systems Inc., Elek Tek and Elek Sen, to exploit the capabilities of these materials in different sectors of the electronics industry [6,7] or the textile industry [8].

Annex lists the main applications proposed for these materials in different sectors. It also makes reference to the researchers, companies, universities or research centres responsible for patents, tests and other tasks involving dissemination, marketing or consultancy services linked to these applications. Some of these proposals have already been tested and are in the commercialisation stage, such as touch switches incorporated into fabrics or into various electronic devices or robot hands, although most of these ideas have not gone beyond the patent stage (some of which are referred to below).

In general, the applications listed in Annex usually use these materials as “all-or-nothing” switches for their simplicity of design and implementation, while for promoting other uses that need quantifying (and thereby promote their expansion in industry), it is very important to characterise and model these materials in depth.

Other researchers have proposed models based on complex quantum phenomena to explain the emission of electrons by the Fowler–Nordheim effect or the Schottky barriers at the polymer–metal interface [3]. While these are highly precise in describing the tunnel effect, they lack the sufficient detail to address other thermo-mechanical aspects that affect the physical properties of the material in question and its capabilities as a transducer.

This paper contains a detailed description of the constituent equation for modelling the behaviour of these materials. It is based on the use of a simple quantum model of a particle breaking through a potential barrier, to which are added effects such as the influence of polymer matrix viscoelasticity on sensor response, the influence of pressure and temperature on the elasticity modulus and the dynamic viscosity of the material, as well as phenomena associated with thermal expansion.

By performing tests under different pressures and temperatures encompassing a wide range of operating conditions for these materials, the constituent equation in question is adjusted and an analysis is made of the goodness of the model proposed, as well as any possible future improvements that will lead to greater precision.

These test results have also enabled certain phenomena linked to the in-service response of QTCs to be analysed, as occurs with the thermostatic positive temperature coefficient, or “PTC effect” [7,9], and the acceptance limits of this behaviour, according to which the electrical resistance of the material shows a linear growth with temperature. This phenomenon was detected previously in other polymer-carbon-black/metal particle conductor composites [10,11].

A detailed knowledge of how the material behaves in the face of different thermo-mechanical effects and having models like the one proposed herein can help with the design tasks for new devices based on the properties of these materials, not only as pressure sensors but also as temperature sensors, as the variations in these magnitudes affect the electrical resistance of QTCs.

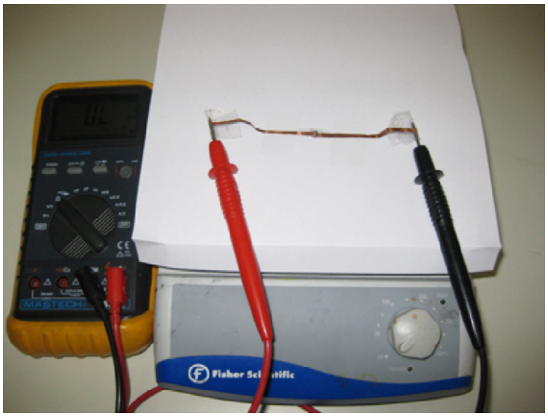

Fig. 2. Test assembly. Sensor on a hotplate connected to a digital voltmeter.

2. Materials and methods

For the detailed studies in this work, tiny 3.6 mm × 3.6 mm × 1 mm QTC pills were taken as the starting point, supplied by the “MUTR Teaching Resources” company (www.mutr.co.uk), in the United Kingdom, associated with Middlesex University (www.mdx.ac.uk). This company also supplies these materials in sheet and cable form for different applications, but here, we have used it in its pill form, which is more suited to analysing combined mechanical, thermal and electrical phenomena.

The sensors used for testing were directly obtained by placing the QTC pills between 75-μm thick Cu sheets and encapsulating them with adhesive tape, as Fig. 1 illustrates, in the same way as proposed by other researchers [7]. Encapsulation was done gently without pre-loading the material, since a pre-load would lead to a somewhat compressed initial situation and would have a lower electrical resistance (by possibly several orders of magnitude). In this event, the sensor would show a smaller range of property variation, and therefore, of measurement, which would limit its range of application. We will assume that the slight thickness of the Cu sheets does not affect the material’s mechanical performance.

To measure the electrical resistance between sensor faces, a “Mastech MY-68” digital multimeter was used with a measuring range of 0.1 Ω to 50 MΩ. So as to be able to conduct tests at different temperatures, a “Fisher Scientific” hotplate was used (as Fig. 2 shows) in combination with a “CME 305” digital thermometer for controlling the test conditions at all times.

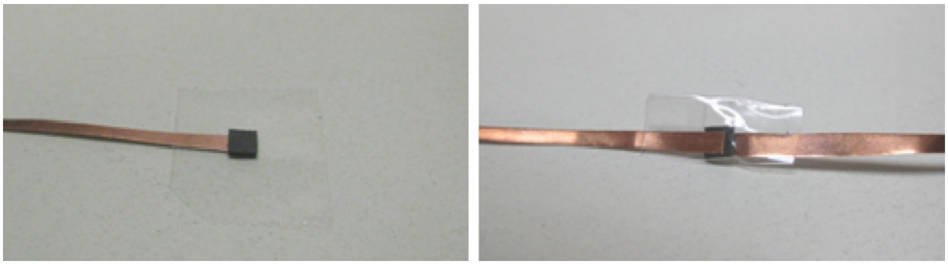

Fig. 1. Pressure sensor based on the use of a QTC pill.