Composites: Part A 59 (2014) 105–114

Contents lists available at ScienceDirect

Composites: Part A

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

Review

Nanotip-induced ultrahigh pressure-sensitive composites: Principles, properties and applications

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A R T I C L E I N F O

Article history:
Received 26 November 2013
Received in revised form 7 January 2014
Accepted 9 January 2014
Available online 18 January 2014

Keywords:
A. Smart materials
B. Electrical properties

A B S T R A C T

Spiky spherical nickel powders with sharp nanotips on their surface are excellent fillers for developing pressure-sensitive composites. The sharp nano-tips are responsible for generating field-assisted tunneling conduction, which leads to the strong responses of electrical conductivity of the composites to external force or deformation. The nanotip-induced ultrahigh pressure-sensitive composites can be used to develop new sensors, switches and controls for a wide range of applications including electronics, transport, space, medicine, defense, textiles, oil and gas, and civil engineering. In this paper, we examine a systematical review of research progress on the nanotip-induced ultrahigh pressure-sensitive composites, with attentions to mechanism of pressure-sensitivity, sensing performances, and applications of the composites. Future challenges in the development and application of the nanotip-induced ultrahigh pressure-sensitive composites are also discussed.

Contents

1. Introduction

The properties of the electrically conductive composites, which are fabricated from insulating polymer or inorganic matrices and conductive fillers, have been studied since the 1950s and continue

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http://dx.doi.org/10.1016/j.compositesa.2014.01.005

to be the focus of theoretical and experimental studies [1–9]. The electrical resistivity of these composites usually decreases under compression as the separation of the fillers decreases, while the electrical resistivity increases when the composites are stretched. This phenomenon is termed pressure-sensitivity, which is also called as piezoresistivity or force-sensitive property. The pressure-sensitive composites fabricated with different matrixes (e.g. rubber, epoxy, ceramic or cement) and different conductive fillers (e.g. carbons including carbon nanotubes, carbon fiber, graphite, pyrolytic carbons and carbon blacks or metals including metal powders, metal fiber or metal oxides) have been developed for various applications [1–15].

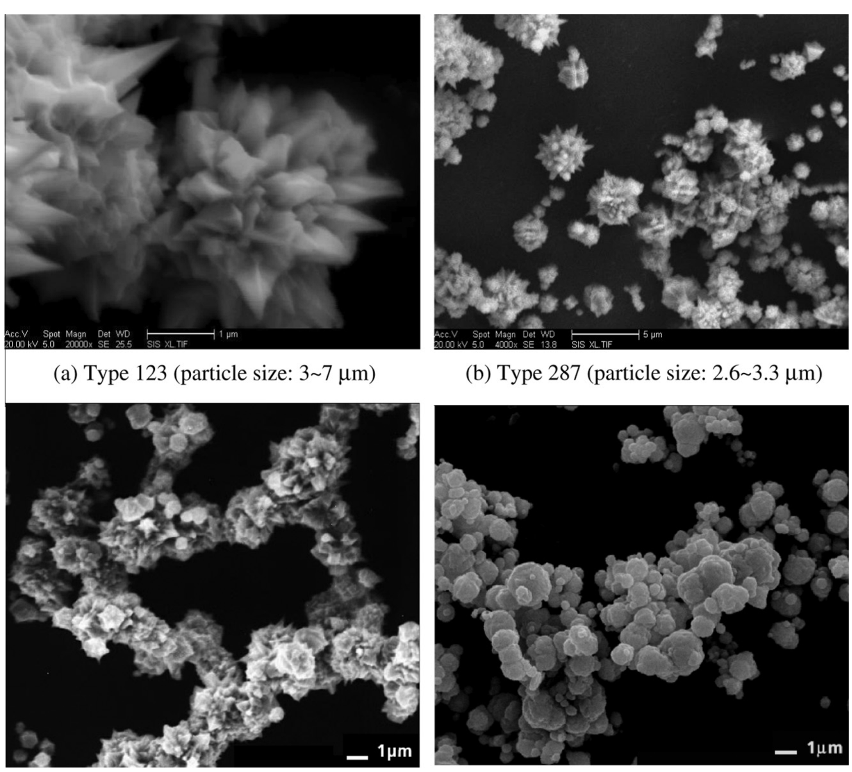
Nickel belongs to the transition metals. It is hard and ductile, which make it very desirable for combining with other metals. Owing to its favorable electrical, thermal, magnetic and magnetostrictive properties and good resistance to corrosion, nickel has been widely used as an effective component or filler to fabricate multifunctional and smart composites with metal or macromolecule material as matrix [7,12,16–20]. Spiky spherical nickel powder possesses sharp surface protrusions similar to the ultra-sharp silicon nanotips or the tips used in field emission microscopy [21–23]. Charge injected into the composite will reside on the filler particles and give rise to high local fields at the tips of the extremely sharp surface features. These nanotips are likely to have field enhancement factors as high as 1000. This will favor field enhanced emission, which is beneficial for enhancing the responses of electrical conductivity of composites to the applied external force [21–25]. The spiky spherical nickel powders were found to be a kind of perfect fillers for developing rubber-based composites with large pressure-sensitive effect in 2005 [12]. The combination of excellent electrical conductance, good resistance to corrosion by caustic alkalis (cement concrete are strongly alkaline with pH of 12–13), perfect mechanical properties and unique spiky surface morphology also makes the spiky spherical nickel powder become an especially promising candidate of fillers for the pressure-sensitive cement-based and epoxy-based composites [26,27].

In the last nearly two decades, much effort has been made towards the advancement of nanotip-induced ultrahigh pressure-sensitive rubber-based, epoxy-based and cement-based composites, and many innovative achievements have been gained in both development and application of nanotip-induced ultrahigh pressure-sensitive composites. The scope of this paper is to examine a systematical review on the main progress and advances of nanotip-induced ultrahigh pressure-sensitive composites and their applications. Future challenges in the development and application of these composites are also discussed.

2. Mechanism of nanotip-induced ultrahigh pressure-sensitive composites

The nanotip-induced ultrahigh pressure-sensitive composites are fabricated by adding spiky spherical nickel powders (as shown in Fig.1a–c) into conventional rubber-, epoxy- or cement-based materials. Their dominant conduction mechanism is the field-assisted tunneling effect. To obtain the pressure-sensitivity, the spiky spherical nickel powders need to be well dispersed in matrix materials through effective processing technology to form an extensive conductive network inside matrix materials (as shown in Fig. 2).

Quantum mechanics shows that electrons can be described as waves under certain conditions, and a finite probability exists of an electron tunneling through a classically forbidden barrier due to its wavelike properties. The amount of the tunneling that occurs in a composite is determined by the energy of the electrons, as well as the thickness and electrical characteristics of the barrier. For tunneling conduction to occur, a higher probability of tunneling



(a) Type 123 (particle size: 3~7 µm)

(b) Type 287 (particle size: 2.6~3.3 µm)

(c) Type 255 (particle size: 2.2~2.8 µm)

(d) Type 110 (particle size: 0.8~1.5 µm)

Fig. 1. SEM photographs of different types of nickel powders [28].