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Piezoresistive TiB_2/silicone rubber composites for circuit breakers

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ABSTRACT

Piezoresistive composites with high hardness and conductivity are required for circuit breakers for multi-cycle operation under large current flow. Based on the simulation results for the mechanical behavior of piezoresistive composites, we developed piezoresistive composites with conductive TiB_2 ceramic materials and silicone rubber. TiB_2 up to 70 vol.% was embedded into the polymer matrix without any mechanical deterioration while the electrical resistance was decreased with increasing TiB_2 content. Piezoresistive composites with 70 vol.% TiB_2 particles exhibited a resistance of 1.7 Ω at a pressure of 1.1 MPa. A circuit breaker with the fabricated piezoresistive composites acted as a switch with a response time of around 2 ms.

1. Introduction

Circuit breakers are electromechanical devices designed to protect an electrical circuit from damage by connecting or disconnecting the power flow at the generator, substation or load location [1,2]. The key factor to piezoresistive-type electric circuit breakers is to develop piezoresistive materials capable of significantly changing the resistivity under external forces. Piezoresistive materials should be easily deformed by an external load, endure multi-cycle operations, carry the load current without excessive heating, and withstand the heat of the arc produced when the circuit is interrupted.

Piezoresistive composite materials can be obtained by compounding an insulating polymer with conductive fillers such as metal particle, carbon black, graphite power, and carbon fiber [3–13]. The high concentration of these conductive fillers could deteriorate the mechanical properties while the low concentration could increase the resistance. Since the high resistance of piezoresistive composites generates joule heating and possibly melting adhesion between the conductive particles, their usage under high current flow condition is prohibited [2,7]. In order to increase their resistance to melting adhesion and life cycle, the use of highly conductive, hard ceramics may be a solution [6].

Metal carbides, nitrides, and borides are groups of ceramics with outstanding and attractive properties for technological applications. Among these materials, titanium diboride (TiB_2) has exceptionally high electrical conductivity and mechanical hardness [6]. Despite these superior properties, reports on piezoresistive composites with TiB_2 are, to the best of the authors' knowledge, very rare. In this experiment, we fabricate TiB_2/silicone rubber composites and characterize the piezoresistive properties for the applied force. Utilizing the fabricated TiB_2/silicone rubber piezoresistive composites, a circuit breaker is fabricated and its response is measured.

2. Experimental procedure

Fig. 1 shows the experimental procedure used to fabricate the TiB_2/silicone rubber piezoresistive composites for circuit breaker application. High purity conductive TiB_2 powder (Alfa Aesar, MA) and room temperature vulcanized (RTV) silicone rubber (GI-1000, Silicones, Inc., NC) were used in this study. The particle size of the TiB_2 was smaller than 325 US mesh (<44 μm). The TiB_2 powder and silicone rubber mixture containing up to 75 vol.% TiB_2 particles was mechanically mixed with a high purity alumina mortar and pestle for over 30 min, and then pressed uniaxially under the pressure of 78.4 kPa at room temperature. The pressed composites were vulcanized by GI-1000 activator for 16 h at room temperature. The rectangular composite blocks were machined to bars of dimensions 3.0 mm × 5.0 mm × 25 mm for the piezoresistivity test. Brass shims, 0.6-mm thick, were bonded on both of the 5.0 mm × 25 mm

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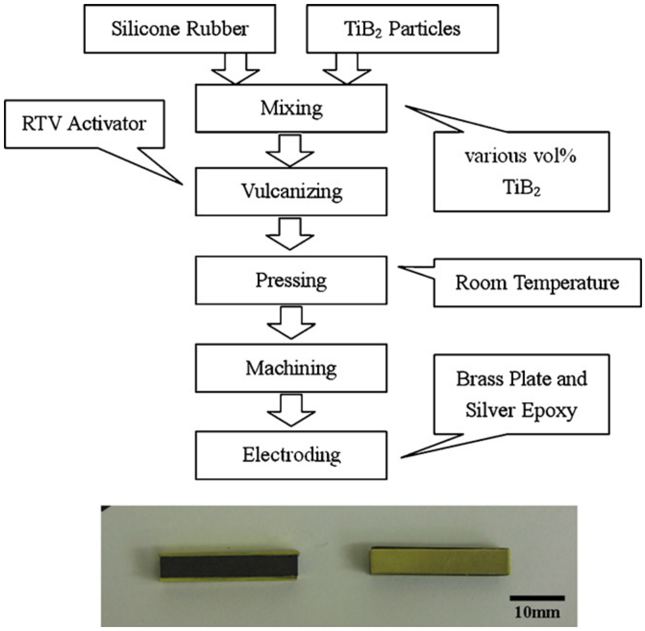

Fig. 1. Schematic diagram of the fabrication of piezoresistive elements and photo of the TiB_2/silicone rubber composite elements.

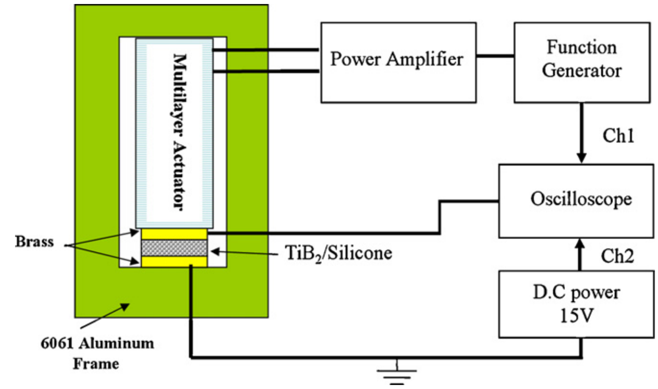

Fig. 2. Schematic of the circuit breaker fabricated with TiB_2/silicone rubber composite and measurement system.

Table 1
Resistivity and hardness of ceramic conductive materials.

Materials	Resistivity ($\mu\Omega$ cm)	Knoop hardness (kg/mm^2)
TiB_2	14.4	3370
TiC	52.5	3200
TiN	25	1994
WC	19.2	1780
ZrB_2	16.6	2252

surfaces with silver epoxy sheet, and then cured at 60 °C for 5 h. The bottom of Fig. 1 shows photo of the TiB_2/silicone composites fabricated by this process. The electric resistivity variations with uniaxially applied force were measured by electro-multimeter (KEITHLEY 175A digital multimeter). The test bars were pressed under several different loads up to 14 kgf (1.1 MPa, 150 psi) and the electric resistivity changes were measured. The microstructures of the specimens were studied by scanning electron microscopy (SEM; JSM-5800, JEOL Co., Tokyo, Japan).

Utilizing the TiB_2/silicone rubber piezoresistive composites, a prototype circuit breaker was designed, as shown in Fig. 2. A multilayer actuator (NEC-TOKIN Co., Tokyo, Japan) and piezoresistive composite were tightened in a 6061 aluminum frame. While applying 15 V to the piezoresistive composite, the external load exerted on the piezoresistive composite was controlled by changing the electric field on the multilayer actuator. As shown in Fig. 3(a), the piezoresistive composite was in the electrically open “OFF” state with an electric field applied to shrink the multilayer actuator. However, when the electric field was applied to expand the multilayer actuator, the multilayer exerted a compressive force on the piezoresistive composite to produce the electrically short “ON” state shown in Fig. 3(b).

3. Results and discussion

As mentioned in Section 1, conducting ceramic powders with low resistivity and high hardness are preferred to avoid the serious arc problem in long-life cycle operations. Hard, metallic, conductive transition metal compounds (carbide, nitride, and boride ceramics) can be considered for our application. The particle compounds selected from the elements of Groups III–VIII in the periodic table are included for those, show conductivity similar to that of like metal particles. The properties of representative, potential candidate, ceramic conductive particles are depicted in Table 1. TiB_2 ceramic particles show promising potential as conductive particles due to their low electric resistivity and high hardness. To ensure the high sensitivity of the piezoresistive composite, polymer materials could be deformed with small stress and change lineally under the external load. Before making the piezoresistive composite, we used two-dimensional finite elements analysis (FEA, ANSYS 5.6.2) to analyze the stress and strain distributions of composites fabricated with various polymer materials, such as polyvinylidene fluoride (PVDF), silicone rubber, low density polyethylene (LDPE), and high density polyethylene (HDPE) elastomers. For FEA, the volume fraction of TiB_2 particle is fixed as 60 vol.% for all composites, and the

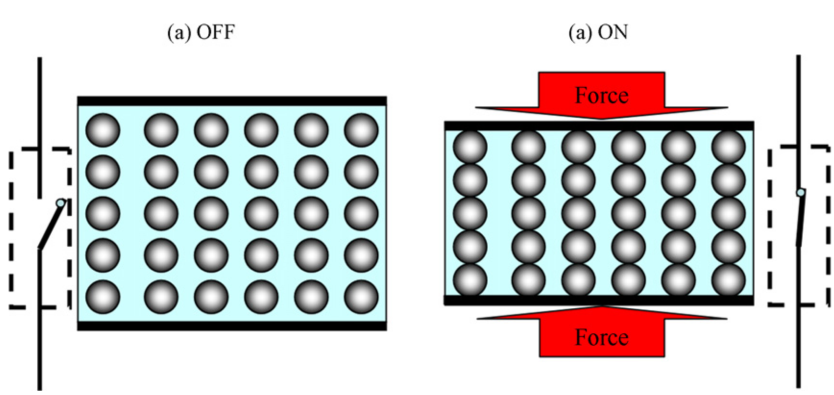

Fig. 3. Schematic illustration of the piezoresistive composite with conducting particles embedded in polymer matrix: (a) under zero stress, each conducting particle is isolated, while (b) under a certain stress, conducting particles are connected.