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Studies on Piezoresistive Property of Thick Film Resistors

***Abstract:* - Purpose**-The paper aims to study the variation of piezo resistivity of the thick film resistors, namely, PVC-graphite /Nickel thick film resistor, with parameters such as volume fraction, grain size, resistor dimension and strain.

Design / methodology / approach – A model is proposed to explain the observed variations, which assumes that the texture of thick film resistor consists of insulator granules coated with conducting particles both graphite and Nickel particles and also having cavities. The resistivity of those resistors is controlled mainly by the contact resistance between the conducting particles and the number of contacts each particle with its neighbors.

Findings- The variation of resistivity with resistor dimension and strain is explained with the help of the model and it is attributed to the change in conducting particles and the number of contacts.

Originality / Value- The variation of resistivity with strain has also been explained with the help of this model and is attributed to the change in number of conducting particles and conducting layers.

Keywords: Films (states of matter), strain, piezoresistivity.

I. INTRODUCTION

A Nanocomposite material based on inorganic and organic components exhibits interesting properties because of electro-mechanical interactions between various phases involved. These materials might lead to the development of resistors for highly sensitive strain sensors. Before any attempt is made to develop these components it is necessary to understand the piezoresistive mechanism involved in these materials. Several investigators have proposed models to explain the piezoresistive conduction mechanism in these materials. Most of the models revolve around the idea that the resistivity of these materials changes with the formation or destruction of conductive networks. Some external factors such as temperature, high voltage and strain can change the conductive network arrangements in the matrix, which results some deformation of conducting networks, leading to a change in the overall resistivity of the resistors. These models explain the variation of resistivity with volume fraction. However, they fail to provide a reasonable quantitative analysis for the resistivity change with grain size, resistor dimensions and strain. In view of this, some experimental investigations have been carried out on PVC-graphite / Nickel thick film resistors to bring out the effect of strain, volume fraction, grain size and resistor dimension on resistivity. First time a model is proposed to explain the observed variations quantitatively and it assumes that the electrical conduction takes place through the contacts between the conducting particles. The variation of resistivity with parameters namely strain, volume fraction, grain size and resistor dimensions is attributed to the change in number of contacts and contact area. The aim of this paper is to report these experimental investigations and the proposed model.

II. EXPERIMENTAL WORK

A. Resistor Fabrication

Thick film paste containing PVC and graphite / Nickel has been prepared by mixing the graphite granules with Nickel nano granules in planetary ball mill for 60 minutes and PVC powder is added to the mixture and again ball

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milling is done for 30 minutes at 1000 rpm. Then cyclohexanone is added to the mixture to form a paste for screen printing. This paste has been used for printing resistors on flexible substrates like PVC substrate and transparent plastic substrate with the help of screen printer supplied by De Haart (Masschachusetts, USA model SP-SA – 05). These printed resistors are processed using usual thick film processing of thick films. This involves drying at room temperature for 15 minutes followed by curing at 100^0C for 4 hours. PVC- graphite / Nickel compositions are taken from 40:60:20 percent (percent by weight of PVC: percent by weight of graphite: percent by weight of Nickel) to 10:90:20 percent. Typical resistor structure is shown in Figure 1.

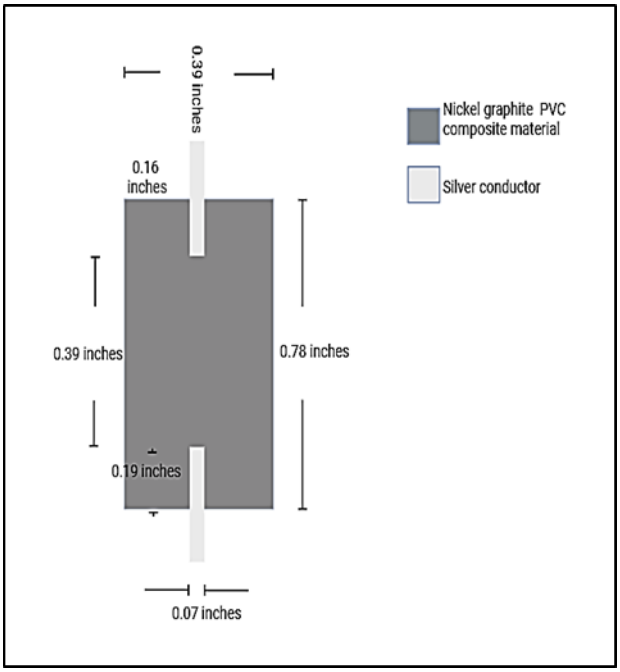

Fig 1: Typical structure of Thick Film Resistor

B. *Strain measurement*

The set-up used to apply forces to the thick film resistors is shown in Figure 2. The electromechanical response of the strain resistors printed on flexible substrates by tensile test is done on a universal test machine 5966. The prepared resistors are stretched with a constant velocity of 0.5 mm/minute on the universal test machine and the resistance of the resistor is noted before stretching. The applied force on the resistor is converted to change in the original resistance which shows the piezo resistance behavior of the resistor. The resistance is measured with digital multimeter.

The gauge factor of the sensor can be calculated using the following equations

$$Gauge\ factor = \frac{\frac{\Delta R}{R}}{\varepsilon} \quad \text{…Eq.1}$$

Where strain, $\varepsilon = \Delta L/L$
Where ΔR is the change in resistance.
R is the original resistance of resistor.
ΔL is extension or change in length for applied load.
L is original length of resistor.

The average value of grain size of the graphite particles used are 10, 45, and 100 µm and the average value of grain size of the Nickel particles is nm. Typical dimensions of this rectangular samples for measurement are length 20 mm and width 10mm and thickness 45 µm. The resistance of each sample has been measured using a Multimeter. The variation of resistivity:

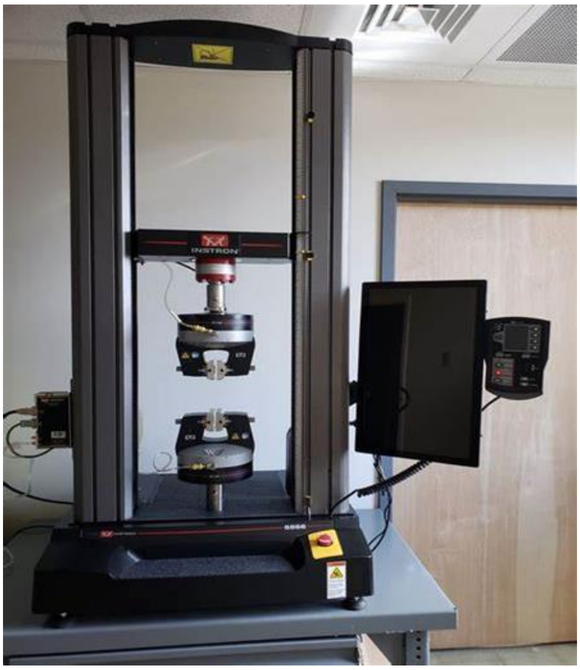

Fig 2: Universal Testing Machine (INSTRON 5966) for the application of strain

- With the volume fraction at different grain sizes;
- With the grain size at different volume fractions;
- With resistor dimensions different volume fractions; and
- With strain at different volume fractions for different grain sizes has been determined.

Typical curves showing these variations are shown in Figures 3-6.

Five resistors of each type are subjected to these measurements and the average resistivity is taken as the resistivity for that resistor.

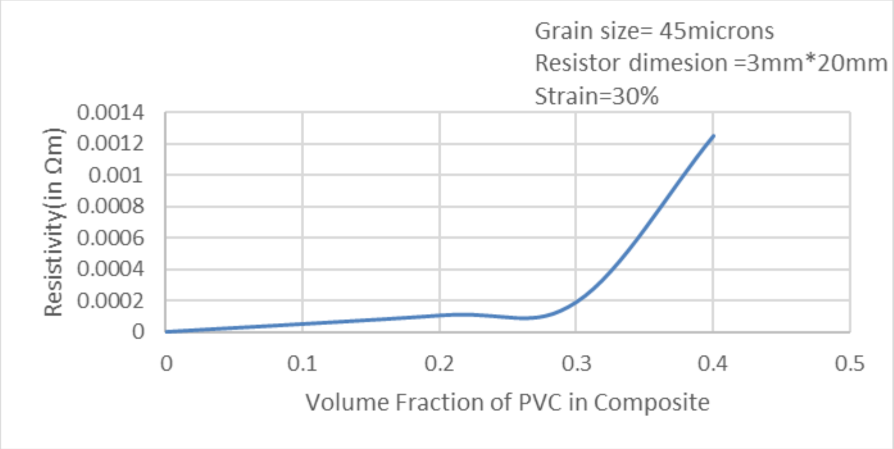

Fig 3: Resistance changes with strain versus volume fraction for a PVC-Graphite/Nickel thick film resistor

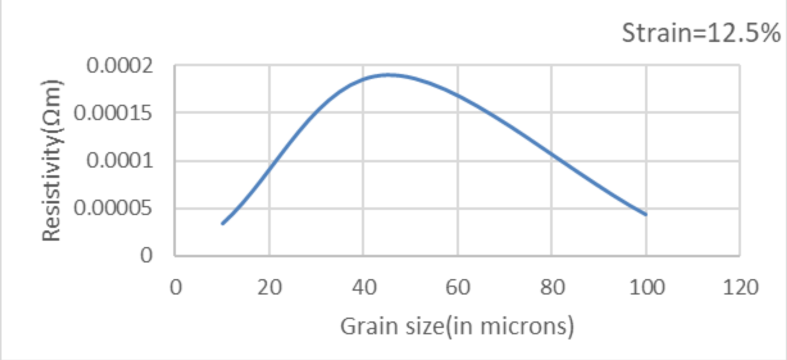

Fig 4: Resistance changes with strain versus grain size for a PVC-Graphite/Nickel thick film resistor

III. RESULTS

A. Variation of resistivity with volume fraction for an applied strain

The electrical resistivity variation with percentage weight of conductor (graphite) is shown in Figure 3. The increase in weight of conductor in resistor composition indicates an increase in volume fraction of conductor in thick film resistor. From Figure 3, it may be seen that the electrical resistivity increases with volume fraction for a particular grain size. From these observations, it appears that the increase in electrical resistivity in these thick film resistors with increase in volume fraction is due to decrease in number of contacts between the conducting particles and the number of conducting chains with an applied strain.

B. Effect of grain size on resistivity with an applied Strain

From Figure 4, it may be seen that the resistivity increases with grain size for a particular volume fraction and an applied strain. From Figure 4, it appears that the resistivity in these resistors is governed by the number of contacts between the conducting particles.

C. Effect of resistor Dimension on resistivity with an applied strain

From Figure 5, it may be seen that the resistivity decreases with resistor dimension for a particular volume fraction and grain size with an applied strain. From Figure 5, it appears that the resistivity in these resistors decreases with an increase in number of contacts between the conducting particles and the number of conducting chains.

D. Variation of resistivity with an applied strain

From Figure 6, it may be seen that the resistivity increases with an increase in applied strain for a particular volume fraction and grain size. The variation of resistivity with an applied strain due to change in contact area between the conducting particles. The resistance between the particles is sensitive to the contact area which changes with strain as a consequence of the expansion properties of insulating phase with applied strain.

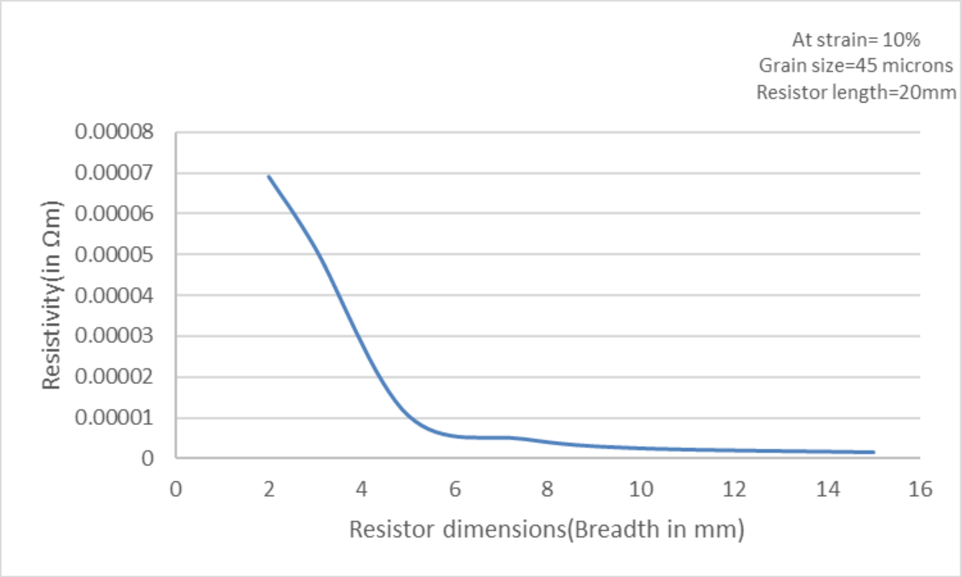

Fig 5: Resistance changes with strain verses resistor dimensions for PVC Graphite/Nickel Thick Film Resistor

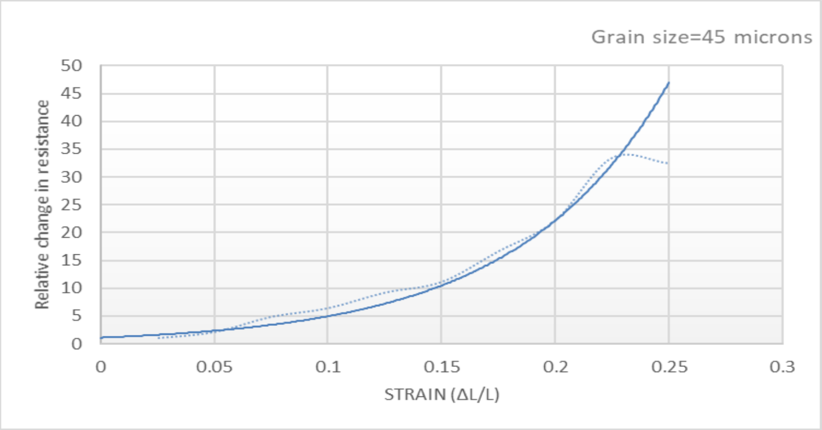

Fig 6: Relative change in resistance with strain for a grain size of 45µm

IV. THE MODEL

In order to estimate the changes in resistance with parameters such stress, volume fraction, grain size and resistor dimensions, a model for the structure of thick film resistive material is proposed and the effect of various parameters such as stress, volume fraction, grain size and resistor dimensions have been evaluated. The following gives an account of this effort.

It has been assumed that small granules of the insulating phases are covered by the particles of conducting phaseses, and such elemental cells constitute the entire composite material. For analytical purposes, it is assumed that the insulating granules are in the form cubes, and the conducting particles are distorted spheres. The cross section of such an elemental cell is shown in Figure 7. Such elemental cells constitute the entire composite material. But thick films contain a large number of cavities. It has been introduced a more realistic picture of insulator with cavities in the elemental cells in order to explain the effect of stress. It has also been assumed that all of the grains are connected in the form of chains.

A typical structure assumed for the material is shown in Figure 8. It may be seen that the material contains conducting graphite chains and Nickel chains surrounding the insulator material with cavities. For simplicity sake it is assumed that there is a unit microcell of the material which contains one cavity and this microcell repeats the entire material. Further, it may be seen that from Figure 8 that the conducting chains are closed throughout the material except at the cavity, i.e. the conducting chains are broken on the surfaces of the cavities. Using this model, the variation of resistivity of the thick film resistor with parameters such as volume fraction, grain size and resistor dimension has been evaluated when an stress is applied to such a material,

The effect of the size of the cavity on the resistance of thick film resistor is calculated using this model. In what follows, is a brief account of the effort that is put into arrive at an idea of resistivity varies with volume fraction, grain size, resistor dimension and stress, and it involves the calculation of chain length, calculation of the resistivity of the material without cavities and with cavities, how to evaluate the effective radius of the cavity after the application of stress and finally calculation of the change in resistance.

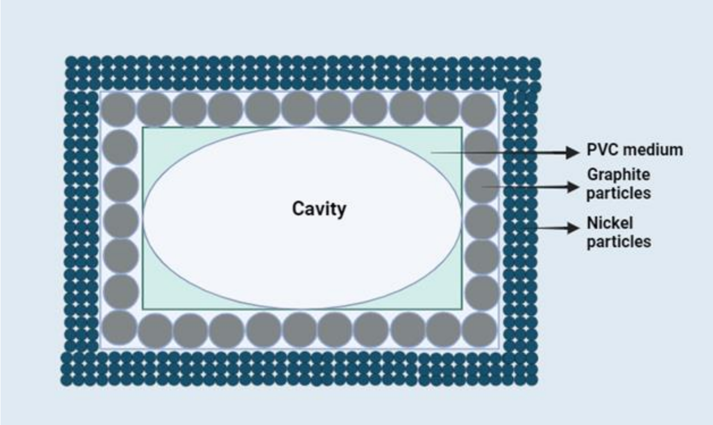

Fig 7: Cross section of an elemental cell of a Thick Film Resistor

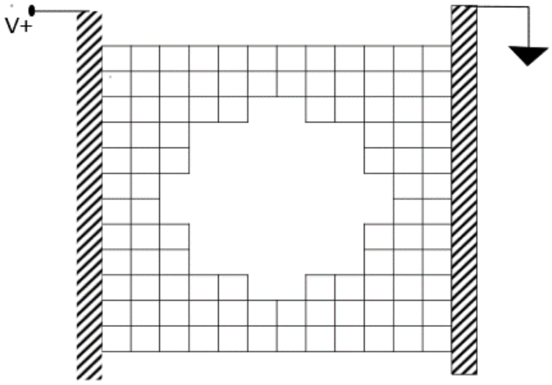

Fig 8: Cross section of a microcell of a Thick Film Resistor

A. Calculation in chain length.

As explained earlier, the composite is assumed to consist of chains of graphite particles and Nickel particles and surround by the insulating medium as shown in Figure 7. The chain length is expected to depend up on compositions of graphite and Nickel and the Insulator. In fact one can guess that the chain length decreases and the number of chains increase with increase in composition. In what follows, is a method of arriving at the chain length of a composite of a given composition.

From the Figure 7, it may be seen that each chain is shared by four adjacent elemental cubes and therefore the amount of graphite in each chain is shared by four cubes. Hence, the graphite due to one chain per cube is one fourth. However, there are 12 chains per cube and therefore the graphite per cube (12*1/4 = 3 chains) is due to the graphite present in the three chains. If the graphite content in each chain Ge is given by Ge = Number of grains in a chain (N)* volume of the graphite granule (VG).

The number of graphite grains "N1" is given by

$$N_1 = \frac{l}{d_1}$$

…Eq 2

Where l = the chain length of the graphite and Nickel chains, d_1 = diameter of the graphite granule which is assumed to be spherical.

The volume of each graphite granule is

$$V_g = \frac{4}{3}\pi(\frac{d_1^3}{8})$$

…Eq 3

Therefore, volume of graphite per cube is

$$\frac{4}{3}\pi\left(\frac{d_1^3}{8}\right) * \frac{l}{(d_1)} * 3 = \pi l \frac{d_1^2}{2}$$

…Eq 4

In the similar lines above, the volume of Nickel grains also calculated as follows:

Number of Nickel grains N_2

$$N_2 = \frac{l}{d_2}$$

…Eq 5

Where l = the chain length of the graphite and Nickel chains, d_2 = diameter of the Nickel granule which is assumed to be spherical.

The volume of each Nickel granule is

$$V_N = \frac{4}{3}\pi(\frac{d_2^3}{8})$$

…Eq 6

Therefore, volume of Nickel per cube is

$$\frac{4}{3}\pi\left(\frac{d_2^3}{8}\right) * \frac{l}{(d_2)} * 3 = \pi l \frac{d_2^2}{2}$$

…Eq 7

Number of elemental cubes per unit micro cell is

$$\frac{L^3 - \pi l \frac{d_1^2}{2} - \pi l \frac{d_2^2}{2}}{l^3}$$

…Eq 8

Where L = length of the unit microcell

Volume of Graphite granules in micro cell is

$$\pi \frac{d_1^2}{2}(\frac{L^3 - \pi l \frac{d_1^2}{2} - \pi l \frac{d_2^2}{2}}{l^2})$$

…Eq 9

Volume of Nickel granules in micro cell is

$$\pi \frac{d_2^2}{2}(\frac{L^3 - \pi l \frac{d_1^2}{2} - \pi l \frac{d_2^2}{2}}{l^2})$$

…Eq 10

$$\frac{Weight\ of\ (Graphite + Nickel)}{Weight\ of\ PVC} = \frac{\left(\pi \frac{d_1^2}{2}\ \rho_G + \pi \frac{d_2^2}{2} \rho_N\right)\left(\frac{L^3 - \pi l \frac{d_1^2}{2} - \pi l \frac{d_2^2}{2}}{l^2}\right)}{(\frac{L^3 - \pi l \frac{d_1^2}{2} - \pi l \frac{d_2^2}{2}}{l^2})(1 - \pi \frac{d_1^2}{2} - \pi \frac{d_2^2}{2})\rho P}$$

…Eq 11

where ρ_G = density of graphite, ρ_N = density of Nickel and ρ_P = density of PVC.

$$\frac{Weight\ of\ (Graphite + Nickel)}{Weight\ of\ PVC} = \frac{\left(\pi \frac{d_1^2}{2}\ \rho_G + \pi \frac{d_2^2}{2} \rho_N\right)}{((1 - \pi \frac{d_1^2}{2} - \pi \frac{d_2^2}{2})\rho_P}$$

…Eq 12

It may be seen from this expression that the chain length “l” decreases with increase in graphite and Nickel contents and is independent of the microcell length or the volume of the microcell (L^3). The effect of cavity is only to reduce the volume of the material in the microcell by an amount equivalent to the volume of cavity.

B. Variation of resistivity with volume fraction

First, it has been calculated the resistivity of the thick film resistors without cavity for a given volume fraction of conducting phases, and then calculated the resistivity of these material with cavities using the technique suggested by Murthy and Satyam.

First it has been calculated the resistivity of microcell covered with only Nickel particles entirely without cavity for a given volume fraction and then calculated the resistivity of the microcell of Nickel particles with cavity and secondly the same procedure is repeated for the calculation of microcell covered only graphite particles without cavity for a given volume fraction and then cavity is introduce in the microcell to evaluate the resistivity of the microcell of graphite particles with cavity. And finally the resistivity of microcell with both Nickel and graphite particles with and without cavities have been evaluated by taking the effective parallel resistances of both microcells i.e. first and second microcells with Nickel and graphite particles with and without cavities.

1) Calculation of the resistivity of thick film resistor without cavity : The Figure 7 shows the cross-section of elemental cell of the thick film resistors. A composite material can be considered as one consisting of insulating cubes covered with conducting particles. It is proposed that the contact resistance between conducting particles control the resistivity of the material. If Rs represents the resistance conducting layers shared between two faces of the adjacent cubes, the electrical equivalent of composite material may be represented by a three dimensional network of resistors, the resistance of each element being Rs. The value of Rs depends on the number of conducting particles per layer, the number of layers, and the contact resistance between two particles. The resistance of conducting layer of conducting particles is directly proportional to the number of contacts in series, and inversely proportional to the number of contacts in parallel. Hence the resistivity of the thick film material can be written as

$$\rho = \frac{1}{2} R_s l$$

…Eq 13

Where *l* is the length of each side of the elemental cell, R_s can be expressed in terms of contact resistance R_0, the volume fraction of the conducting phase V_f and the grain size D of the conducting particles as follows:
If *n* is the number of conducting particles in a row extending over a length *l*, its resistance R_1 is given by

$$R_1 = R_0(n-1)$$

…Eq 14

Where R_0 is the contact resistance between two conducting particles. Since n≫ 1, R_1 can be written:

$$R_1 = R_0 n$$

…Eq 15

When there are two rows, each particle has two contacts and therefore the relative resistance of each row of particles is ½ (R_0n). The effective relative resistance of two rows is ¼ (R_0n).
The resistance of a layer having M rows can be written as

$$R_H = \frac{R_0 n}{(3M-2)}$$

…Eq 16

Similarly, the effective resistance of L layers can be written as

$$R_s = \frac{R_0 n}{(3M-2)(3L-2)}$$

…Eq 17

Where L is the number of layers of the conducting phases shared between two faces of the adjacent elemental cubes. The value of L at a given volume fraction Vf can be arrived at as follows:
The volume of the conducting phase per elemental cell is given by:

$$V_c = \frac{4}{3}\pi R3(\frac{l^2}{\pi R2})(3L)$$

…Eq 18

The volume of the elemental cell is

$$V_c + V_l = l^3$$

…Eq 19

Using equations (18) and (19) one can arrive at:

$$L = \frac{lV_f}{2D}$$

…Eq 20

Where D is the average diameter of the conducting particles, which is also considered as the grain size of the conducting particles. The value of n can be written as n = l/D. Substituting for n and L in equation (17) one can write:

$$R_s = R_0 l \left[D \left(\frac{3l}{D} - 2 \right) \left(\frac{3lV_f}{2D} - 2 \right) \right]^{-1}$$

…Eq 21

The contact resistance between two spherical particles is given by (ref):

$R_0 = \rho_g / 2r$

Whereρ_g is the resistivity of the conducting particles and r is the mean contact radius of the contact area between the conducting particles.

It may be noted that equation (21) has been derived by considering the total number of contacts that come in to picture for electrical conduction. The total number of contacts has been calculated by considering the number of contacts in a layer and the number of layers L between the adjacent cubes of the insulating phase.

Writing:

$$\frac{3l}{2D} = \frac{2}{K}$$

…Eq. 22

One obtains for resistance:

$$R_S = R_0 K [3(2 - K)(V_f - K)]^{-1}$$

…Eq 23

Using equations (13) and (19) the resistivity of the thick film material can be written:

$$\rho = \frac{K_0}{V_f - K}$$

…Eq 24

Or

$$\sigma = \frac{V_f - K}{K_0}$$

…Eq 25

Where $K_0 = \frac{R_0 K l}{6(2-K)}$, K being the constant of a material which depends up on the grain size D. Equation (25) indicates that a plot of conductivity versus volume fraction of the conducting phase should be a straight line. A typical conductivity versus volume fraction curve for a grain size is shown in Figure 10.

2) Calculation of resistivity of thick film resistors with cavities: The variation in resistance with change in diameter of the cavity has been calculated following the lines described by Murthy and Satyam (1985) and is reproduced in the Figure 9. They have given variation of normalized resistance with cavity diameter of thick film resistors. Using this technique the resistance of the thick film resistors with cavities has been calculated.

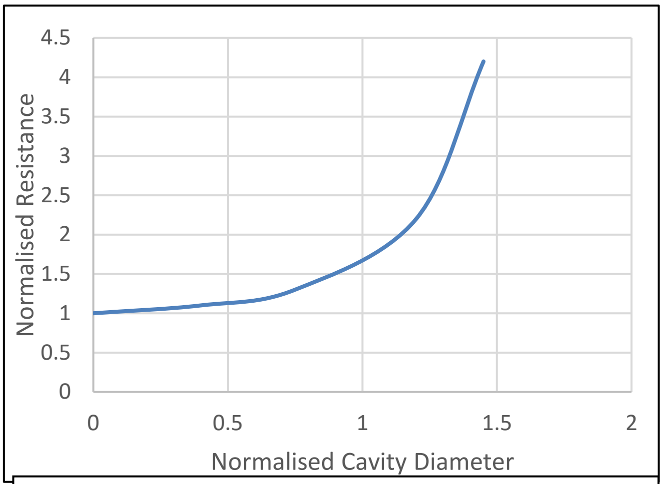

Fig 9: Variation of Normalised Resistance with normalised cavity diameter of a Thick film Resistor

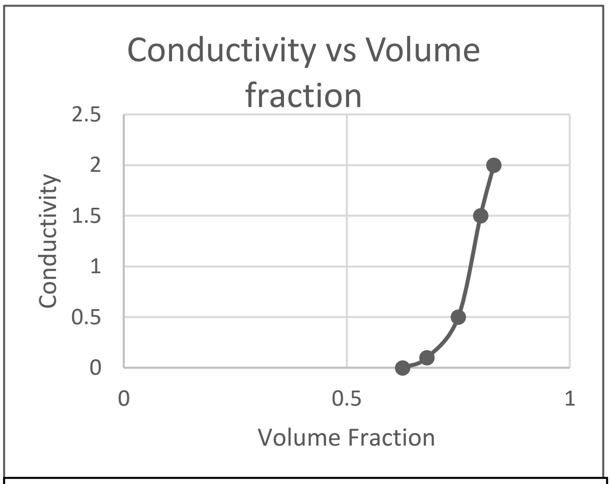

Fig 10: Conductivity versus volume fraction for a PVC Nickel Graphite thick film resistor

C. *Calculation of Resistivity with Strain*

The resistivity change in piezoresistive composites is mostly attributed to the geometry change of the material resulting from the applied external stress. To calculate the exact change we assumes prismatic bar of uniform rectangular section. Then we can calculate the resistance of the composite using the formula below which is derived from Ohm's Law.

$$R = \rho \frac{L}{A}$$

…Eq 26

Where ρ is original resistivity, L is the composite length and A is the cross-section area of the current flow. The conceptual diagram of this process is shown in Figure 11.

Within a certain range of strain this relationship is linear, so that the piezoresistive coefficient ρ_σ is constant and can be expressed as

$$\rho_\sigma = \frac{\frac{d\rho}{\rho}}{\varepsilon}$$

…Eq 27

Where$d\rho$is the change in resistivity, ρ is the original resistivity and ε is strain.

Differentiating (26), we obtain

$$dR = \frac{\rho}{A} dL + \frac{L}{A} d\rho + \frac{\rho L}{A^2} dA$$

…Eq 28

Dividing the (28) by the resistance R yields

$$\frac{dR}{R} = \frac{dL}{L} + \frac{d\rho}{\rho} + \frac{dA}{A}$$

…Eq 29

The relative change in length or the axial strain as

$$\varepsilon_{axial} = \frac{\Delta L}{L}$$

…Eq 30

and lateral strain as

$$\varepsilon_{lateral} = \frac{\Delta W}{W} = \frac{\Delta H}{H}$$

…Eq 31

The Poisson's ratio is

$$V = -\frac{\varepsilon_{axial}}{\varepsilon_{lateral}}$$

…Eq 32

The relative resistance changes as a function of strain and resistivity

$$\frac{\Delta R}{R} = (1 + 2V)\varepsilon_{axial} + \frac{d\rho}{\rho}$$

…Eq 33

The gauge factor (K) of a piezoresistive material is defined as the fractional change in resistance per strain

$$K = \frac{\frac{\Delta R}{R}}{\varepsilon_{axial}} = (1 + 2V) + \frac{\frac{\Delta\rho}{\rho}}{\varepsilon_{axial}}$$

…Eq 34

$$Guage\ factor_{composite} = \frac{\frac{\Delta R}{R}}{\varepsilon_{axial}} = \frac{\frac{\Delta\rho}{\rho}}{\varepsilon_{axial}}$$

…Eq 35

For composites, many external factors including mechanical, thermal or even environment can lead to change in the electrical resistivity. In most cases, the main factor is the change of the internal composite structure such as the between-filler distance, number of the contact points and contact points density. With any of those above mentioned factors applying to the composites, changes inside the structure including breakdown of the filler junctions or reformation of the conducting network by rotation / alignment/ translation could take place. The final dominant mechanism of the composite depends on various factors such as polymer type, filler type, concentration, geometry, filler orientation-dispersion, amplitude, direction and type of external factor, measurement configuration.

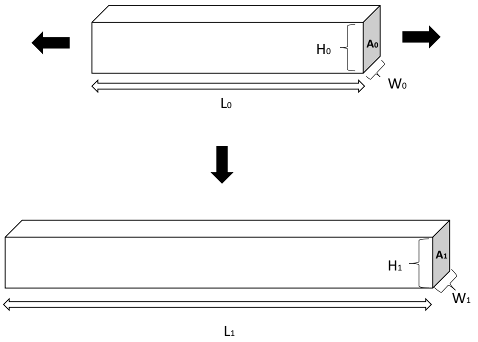

Figure 11 Illustration of Peizoresistivity due to geometry

D. Effect of grain size on resistivity with an applied strain

The resistivity variation with grain size on the application of strain is expected to arise from the change in number of conducting particles in a layer and number of such layers between the electrodes. The resistivity increases with increase in grain size for a particular volume fraction with the application of strain is due to both reduction in number of conducting particles in a layer and number of layers between the electrodes.

E. Effect of resistor Dimension on resistivity with an applied Strain

The resistivity variation with resistor dimension on the application ofstrain is expected from the change in contact area between the conducting particles. This changes the contact area arises because of expansion of the insulating phase and can be related to the expansion coefficient of the insulating phase.

F. Variation of resistivity with an applied Strain

When a particular strain above the threshold value is applied to the resistor, some of the closed chains break depending on time and the amount of strain that is applied. Owing to the breaking of the conducting chains, the diameter of the cavity of thick film resistors increases. The variation of resistance with change in diameter of the cavity has been calculated using the method suggested by Murthy and Satyam.

V. CONCLUSION

The variation of pizoresistive property like electrical resistivity of a typical thick film resistors, namely PVC-graphite / Nickel thick film resistors with parameters such as volume fraction, grain size, resistor dimension and strain has been studied. The expressions for the electrical resistivity of thick film resistors in terms of volume fraction of the conducting phase (graphite and Nickel), grain size of the conducting particles and contact resistance have been derived. There is a good agreement between the observed result and those predicted by the model. The variation of resistivity with volume fraction and grain size is due to the change in number of contacts between the conducting particles. The variation of resistivity with resistor dimension is due to the change in contact resistance, which is brought about by the expansion of insulating phase. Thus, it appears that resistor dimension change of thick film resistor with strain can be controlled by the expansion properties of insulating medium. The variation of resistivity with strain is due to increase in number of conducting chains due to mechanical forces, which arise with the application of strain.

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