ELECTRICAL RESISTIVITY AND CONTACT RESISTANCE OF ELECTRICALLY CONDUCTIVE SILICONES

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ABSTRACT

Cable accessories for medium- and high voltage applications contain field grading and field zoning parts or layers. These parts often consist of electrically conductive silicone elastomers. The electrical conductivity is achieved by using selected and long-term tested carbon blacks.
Conductive layers and parts are used to provide safety against exposure, inner shielding and an electrical contact to metallic parts of earth connectors.
The paper describes the measuring technology of the electrical resistivity of carbon black filled silicone elastomers and of the resistance of electrical contacts between carbon black filled elastomers and metallic contact parts. Service relevant stress parameters such like current load of the elastomer, storage at elevated temperature and elongation of the rubber are systematically investigated with respect to their short- and long-term influence on the volume resistivity of silicone specimens.
An adjustable model equipment is used to investigate processes in the contact between conductive silicone specimens and metallic contact partners. The contact status is evaluated by measuring the contact voltage in dependence of the time.
Evaluated electrically conductive silicone elastomers are found to show a long term stable electrical conductivity, even at a current density that is by far higher than under service conditions. Neither the elongation of the specimens nor the storage at elevated temperature leads to significant changes of the resistivity.
It is possible to achieve a reliable electrical contact between electrically conductive modified silicone rubber and metallic contact partners. Precautions are needed with respect to the design of the contact, the contact area and the contact force to ensure a safe long-term availability.

INTRODUCTION

Carbon black-filled silicone elastomers with a specific volume resistivity in the range of (1 … 100) Ωcm are used for field grading and field zoning applications (Fig. 1), [1]. [1]
Both conductive layers as well as the electrical contact system of the terminal lug need to be able to carry the capacitive current in the range of some 100 µA to some milliamps. The terminal lug contact system consists of a conductive silicone rubber and metallic parts, such like cable lug, washers, bolt and nut. Thus, a reliable service life of a connector (and corresponding components) requires both, a long-term stable resistivity of the silicone rubber as well as of the electrical contact of the terminal [2].
Relevant stress factors are independently investigated to collect reliable data.

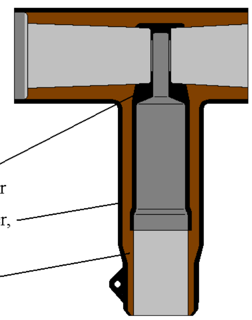

Fig. 1. Medium voltage elbow connector (principle sketch after [3])

EXPERIMENTAL PROCEDURE

4-wire Method to Measure the Specific Volume Resistivity

An accurate measurement of the specific volume resistivity of electrically conductive synthetic materials (specific volume resistivity $\rho < 10^6$ Ωcm) requires the application of the 4-wire method like it is used for metallic materials [4].
The main advantage of the 4-wire method is a separation of the current feed and the voltage probe electrodes. Provided the electrode distance is chosen in a way that the voltage probes are located in the homogeneous part of the electrical flow field there is no influence of the electrical contact resistance of the current electrodes on the measuring result.
Hence for a distance of the current electrodes of 100 mm, the distance between the voltage probes is 20 mm and the distance between the voltage probes and the current electrodes is 40 mm.
The experimental set-up for plate-shaped specimens was built on the basis of the recommendations of DIN EN ISO 3915, [5], (Fig. 2).
The specific volume resistivity is calculated after (1) where ρ is the specific volume resistivity, R_x is the measured resistance; A is the cross sectional area of the specimen and d is the distance between the voltage probes.

[1] silicone rubber with a high permittivity is used for refractive field grading applications.

$$\rho = R_x \cdot \frac{A}{d} \qquad (1)$$

The application of the 4-wire method allows an accurate and repeatable evaluation of the specific volume resistivity of electrically conductive silicone elastomers [4].

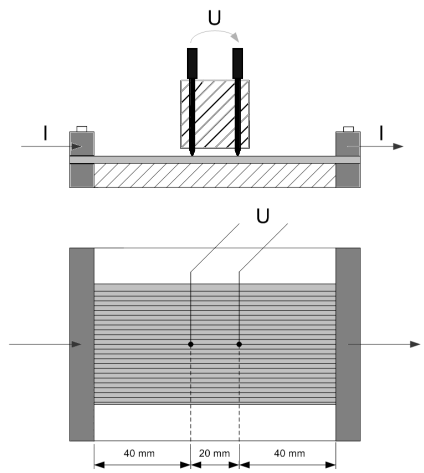

Fig. 2. 4-wire method for the measurement of the specific volume resistivity of electrically conductive modified silicone elastomers in principle

Model arrangement for the Evaluation of the Contact Resistance

The contact resistance is no material property but depends on the macroscopic and the microscopic geometry of the contact as well as on the contact force and on contact layers, e.g. corrosion or pollution layers (hereupon referred to as layers).

Thus, a contact resistance R_c consists of the skin resistance R_{sk} and the constriction resistance R_{co}, [6], (2):

$$R_c = R_{sk} + R_{co} \qquad (2)$$

The termination contact of a connector with a layer is modelled to allow the variation of the geometry of the contact as well as the contact force and thus the contact resistance R_c. The principle is shown in Fig. 3.

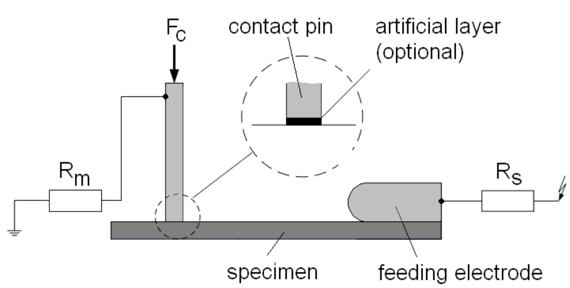

Fig. 3. Model arrangement in principle; R_s is the series resistor of 1 MΩ, R_m is the measuring resistor (shunt) of 100 Ω, F_c is the contact force

A current is forced through series resistor R_s and the feeding electrode into the specimen and flows through the contact pin and a measuring resistor R_m to ground. The contact pin may wear a layer and is actuated by a spring in a way that it pushes with an adjustable force of less than 300 N against the specimen.

INFLUENCE OF EXTERNAL STRESS FACTORS ON THE VOLUME RESISTIVITY OF CONDUCTIVE SILICONE ELASTOMERS

Capacitive current, thermal and mechanical loads are typical stresses silicone cable accessories are exposed to.

To investigate the influence of the current on the specific volume resistivity specimens with a cross sectional area of 150 mm^2 are exposed to a stepwise increased current (1 mA/30 s). The chosen current of 50 mA is a multiple of the typical load and equals to 333 µA/mm^2. The current is then decreased with the same velocity.

No changes in the volume resistivity of the tested silicone rubber and no warming are found. No influence of the type of stress (AC/DC) is detected. A 33 µA/mm^2 long-term stress does not cause any significant change of the specific volume resistivity either.

Specimens of conductive silicone elastomer are stored for more than 4500 h at an elevated temperature of 80 °C to simulate a typical thermal stress. The specific volume resistivity is measured discontinuously.

The specific volume resistivity remains stable over the storage time with a tendency to a slight decrease. It can be concluded that typical thermal stresses do not cause changes of the evaluated silicone elastomer. See [7] for details.

Cable accessories are typically exposed to an elongation when being mounted. A typical elongation is in the range of 50 - 100 %. Cold shrink applications require a wider elongation up to 300 %.

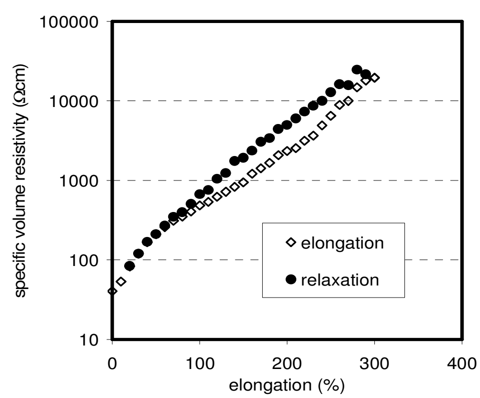

Fig. 4. Specific volume resistivity in dependence on the elongation

Shouldered test bars are used to evaluate the specific volume resistivity under elongation. These bars are stressed up to an elongation of 300 % at a rate of 10 % per 30 s. The direction of the stress was parallel to the electric field. Elongation is decreased at the same speed and the specific volume resistivity is measured (Fig. 4).

An elongation of the evaluated material leads to an increase of the specific volume resistivity which is caused by a deformation of the percolation network. The stepwise

decrease of the mechanical stress leads to a restoration of the initial state although there is a slight hysteresis.
To allow a better understanding of this effect a long term test is carried out. Specimens are kept expanded over 100 h. The following values of the volume resistivity are measured (Fig. 5).

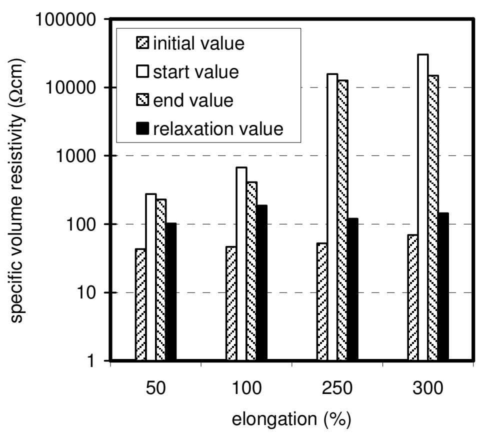

Fig. 5. Specific volume resistivity before, during and after a long-term elongation
initial value: value without elongation,
start value: value at the initial elongated stage,
end value: value at the end of the elongation period,
relaxation value: value after 100 h of relaxation.

As expected, the start value at the initial elongated stage is the higher the higher the elongation of the specimen. The end value is found to be lower than the start value. This as well indicates that there are formation processes in the percolation network. The relaxation values are measured to be higher than the initial values. Nevertheless, the specific volume resistivity of the evaluated material remains in a range of 100 Ωcm (volume conductivity of 1 S/m respectively).

CONTACT BEHAVIOUR OF METALLIC ELECTRODES AND SILICONE ELASTOMERS

Contact Force

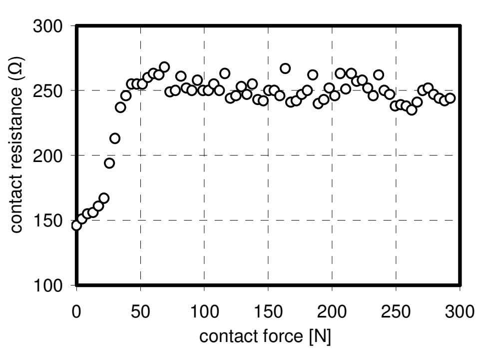

Fig. 6. Specific volume resistivity before, during and after a long-term elongation

The contact force of a brass electrode against a silicone rubber specimen is increased from 0 N up to about 300 N by steps of 4 N.
In the difference to metallic contacts the increase of the contact force leads to an initial increase of the contact resistance. Further increase of the force has no further impact on the resistance (Fig. 6). It is assumed that this is caused by both, a deformation of the specimen and changes of the effective contact area.
As the contact resistance consists of the constriction resistance and the skin resistance, we asked ourselves what the effect of a layer is. A field calculation is done understand the situation.

Electrical field of a model contact

A terminal lug of a connector with a metal bolt, washers and nut is modelled (Fig. 7).

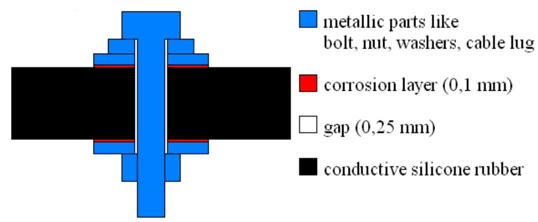

Fig. 7. Model for the computation of the electrical field of a terminal lug

Electrical conductivity of all metallic parts is defined to be $1{,}5 \cdot 10^{7}\, Sm^{-1}$. The current burden is selected to be 1 mA. In case of a sound contact, the conductivity of the layer is defined to be 10^{-1} S/m, the conductivity of the conductive rubber is defined to be 1 S/m (100 Ωcm), the current flows through the contact area between the silicone rubber and the washers and originates there a low maximum field strength of less than 0,05 V/mm (Fig. 8).

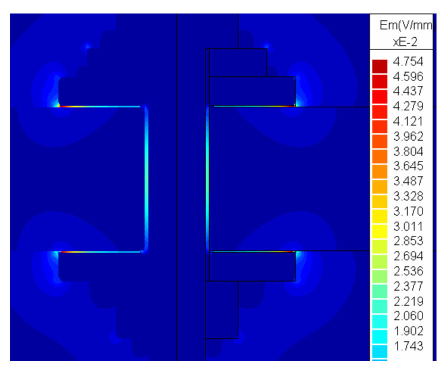

Fig. 8. Electrical field strength distribution originated by a current burden of 1 mA through the conductive silicone (1 S/cm) and a low resitivity layer between the rubber and the washer (10^{-1} S/m)

An increasing resistivity (decreasing conductivity) of a layer leads to a strong increase of the field strength in the contact (Fig. 9). The calculated maximum field strength of about 1,3 kV/mm is definitely in a critical range with respect to the probability of an ignition of electrical discharges in the layer.

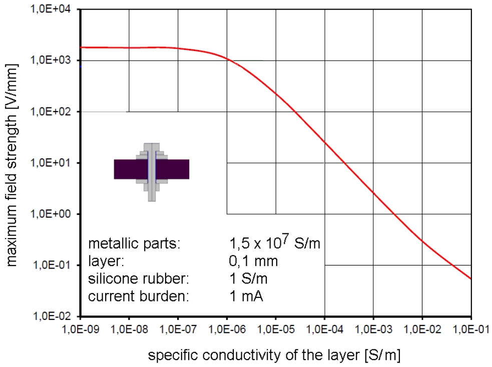

Fig. 9. Maximum electrical field strength in the contact in dependence on the specific conductivity of the layer

Modern computation allows an evaluation of the influence of all possible material combinations. Thus a “compen-sation” by using a silicone rubber with a higher conductivity can be theoretically taken into consideration. Fig. 10 shows the influence of the conductivity of the elastomer on the maximum field strength in case the layer is highly resistive.

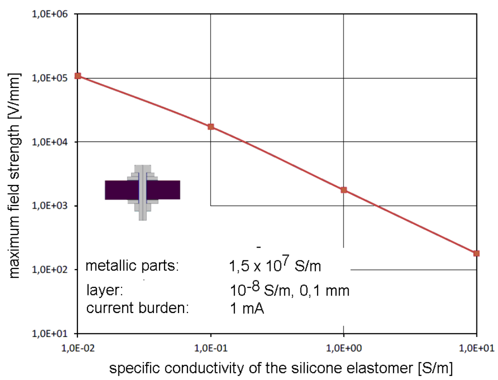

Fig. 10. Maximum field strength in a contact with highly resistive layer in dependence on the specific conductivity of the silicone elastomer

Experience shows that no contact will survive if the contact resistance is high [2]. That is why the “compensation approach” is not a viable solution.

SUMMARY AND CONCLUSIONS

Specimens of an electrically conductive modified silicone rubber are exposed to a current that is more than 10 times as high as it is in service. Test pieces are stored at 80 °C for a long time. The specific volume resistivity of the evaluated silicone elastomer for medium voltage applications is neither affected by the current nor by a thermal stress.
Shouldered test bars are elongated to a maximum elongation of 300 %. The higher the elongation the higher is the volume resistivity. A long term elongation may lead to a negligible increase of the remaining volume resistivity. The material remains applicable.
The behaviour of the contact system metal-conductive silicone rubber is different than that of metal-metal contacts with respect to the influence of the contact force in the contact resistance. A computation of the electrical flow field of a terminal lug shows that a layer at the surface of the metallic parts leads to a strong increase of the field strength in the contact system.
Contact systems of metallic parts and conductive silicone rubber need to be designed in a way that the contact resistance remains as low as possible. A high contact force does not necessarily lead to a low contact resistance.

A layer on the surface of metallic partners may lead to a strong increase of the electrical field strength which may lead to partial discharges that can deteriorate the conductive silicone rubber. Hence, the use of corrosion-resistant metallic contact materials and contacts with a sufficient contact surface are recommended.

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