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Development and characterization of conductive silicone rubber for electro active polymer generators

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Abstract

This work investigates the development and characterization of conductive silicone rubber for the use in electro active polymer (EAP) generators. EAP generators have to withstand extremely high mechanical and electrical stresses during operation, so the electrical resistance inside the thin elastomeric electrode has to stay almost constant during operating time. Therefore, two different silicone binders with various crosslinking densities have been developed to investigate the different behavior during dynamic cycle stress. Each silicone material is formulated with the same amount of carbon black to ensure good electrical resistance, even under 100 % strain. Crosslinking density is derived by measuring Shore A hardness and the dissipation factor inside a dynamic mechanical test. Material D1-2 with a Shore A hardness of 27 and a dissipation factor of 0.320 and material D2 with Shore A hardness of 42 and a dissipation factor of 0.032 have been examined. For testing, a 3 layered sample is prepared, the developed conductive silicone layer in the middle, covered by insulating commercial silicone material. The high mechanical stress is simulated with an eccentric drive to create a linear motion with sinusoidal excitation at a frequency of 5 Hz. The samples are clamped with a preload of 10 % and become stretched to a maximum of 110 % elongation, while measuring the electrical resistance both at minimum and maximum strain. Silicone material D1-2 shows an increase of resistance of nearly 439 % over one million cycles, while silicone material D2 shows only an average increase of 80 %. Thus, the damage inside the conductive layer depends on the crosslinking density of this layer and results in different resistance behavior after testing one million cycles.

Introduction

Electro active polymer (EAP) generators have to withstand extremely high mechanical and electrical stresses during operation. For economic operation of the generator, more than one million mechanical stress cycles are required. Highly accelerated life tests with a frequency of 5 Hz up to 1 million stress cycles have been specified to get significant results in a short period of time. Especially the electrical conductive silicone layer has to show a very high conductivity or rather a low resistance, which has to stay almost constant during the test period. Therefore, silicone material has been developed to fulfill the requirements for a conductive layer within an EAP.

Material development

Two different silicone rubber materials, filled with the same amount of carbon black, have been developed in order to get a soft and stretchable conductive layer (= electrode) and to fulfill the mechanical and electrical requirements. The silicone rubber consists of the following components:

- Base polymer: linear, vinyl functionalized polydimethylsiloxanes (PDMS)
- Chain extender: SiH terminated PDMS
- Crosslinker: PDMS comprising SiH groups along the polymer chain

By varying the amount of each component, different crosslinking density can be adjusted. The crosslinking density is characterized by measuring Shore A hardness and determining the mechanical loss factor by measuring a frequency sweep with a shear deformation of 0.1 %.

Sample production and experimental setup

Figure 1 shows a sample for the dynamic-mechanical test (left side) with the following dimensions and characteristics (right side):

- Sample dimensions: 110 mm x 46 mm
- Stretched dimensions of conductive layer: 80 mm x 42 mm
- Electrical connection inside the mechanical clamp
- Diagonal path of the resistance measurement

The sample has three layers, consisting of two protective layers (electrically insulating, transparent) and one conductive layer between them. Each layer is produced by doctor blading the liquid material on glass substrate and thermal crosslinking. A mask is used to realize the geometry of the conductive layer, which has a thickness of approx. 30 µm. Finally, the sample is cured for 18 hours at 120 ° C and cut with a scalpel.

Figure 2 shows the testing device for the mechanical and electrical characterization of up to eight samples simultaneously. The mechanical stress is simulated with an eccentric drive to create a linear motion with sinusoidal excitation at a frequency of 5 Hz. The samples are clamped with a preload of 10 % and become stretched to a maximum of 110 % elongation, while measuring the electrical resistance both at minimum and maximum strain. With this setup, the electrical behavior of the conductive layer during the first million cycles can be measured.

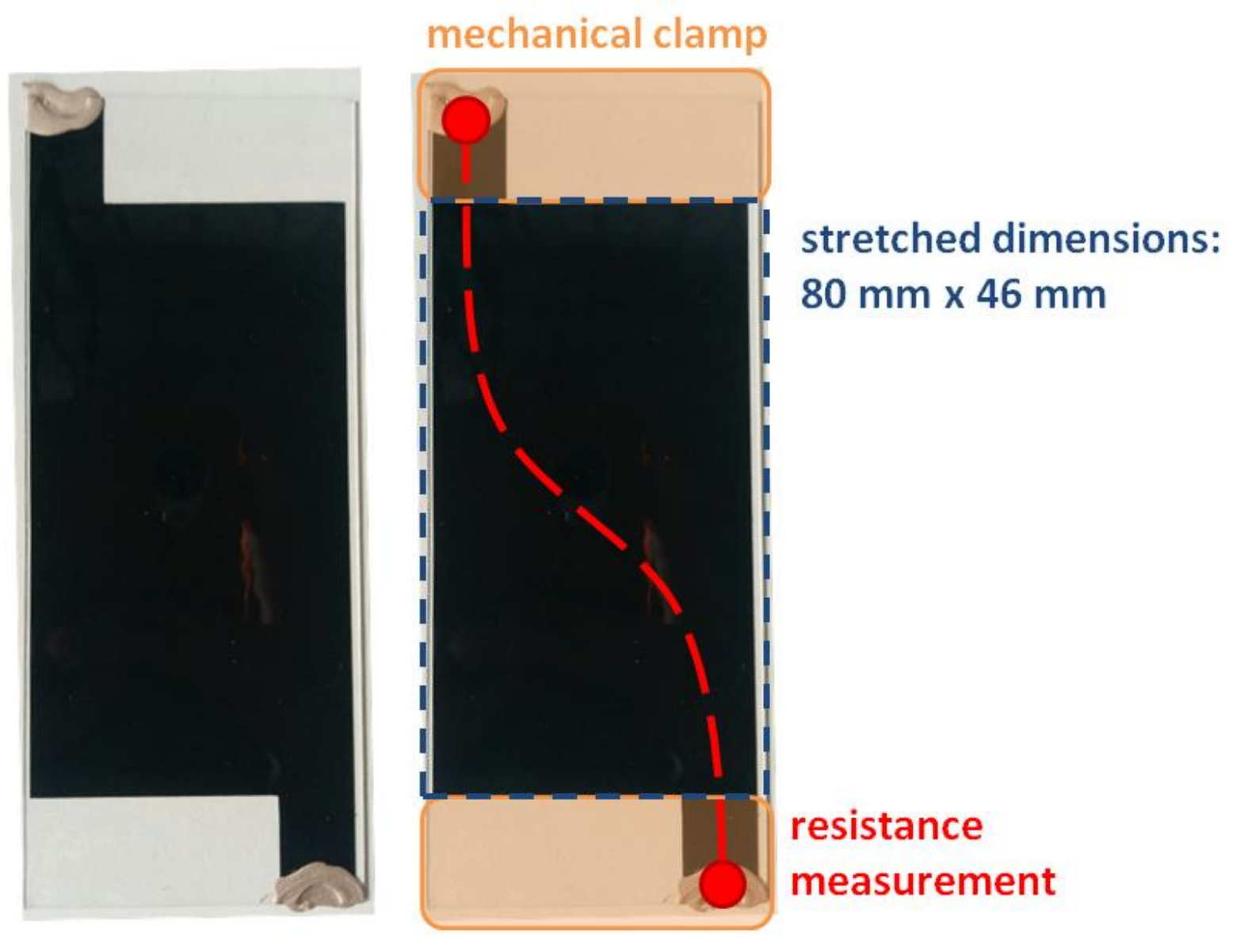

Figure 1: sample for the dynamic-mechanical test

Figure 2: test device for dynamic-mechanical stress

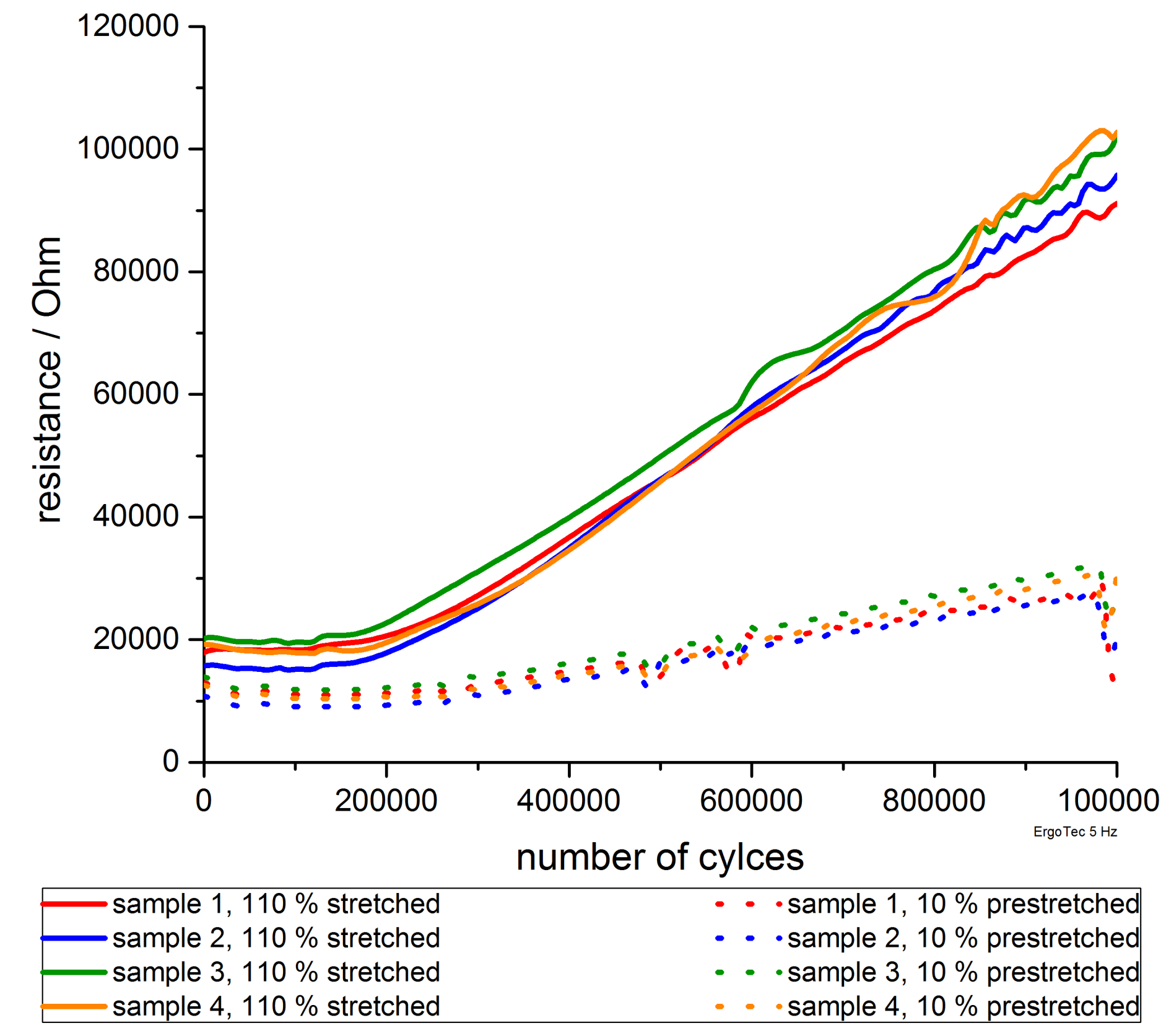

Figure 3: electrical resistance as a function of number of cycles, stretched and unstretched for conductive material D1-2

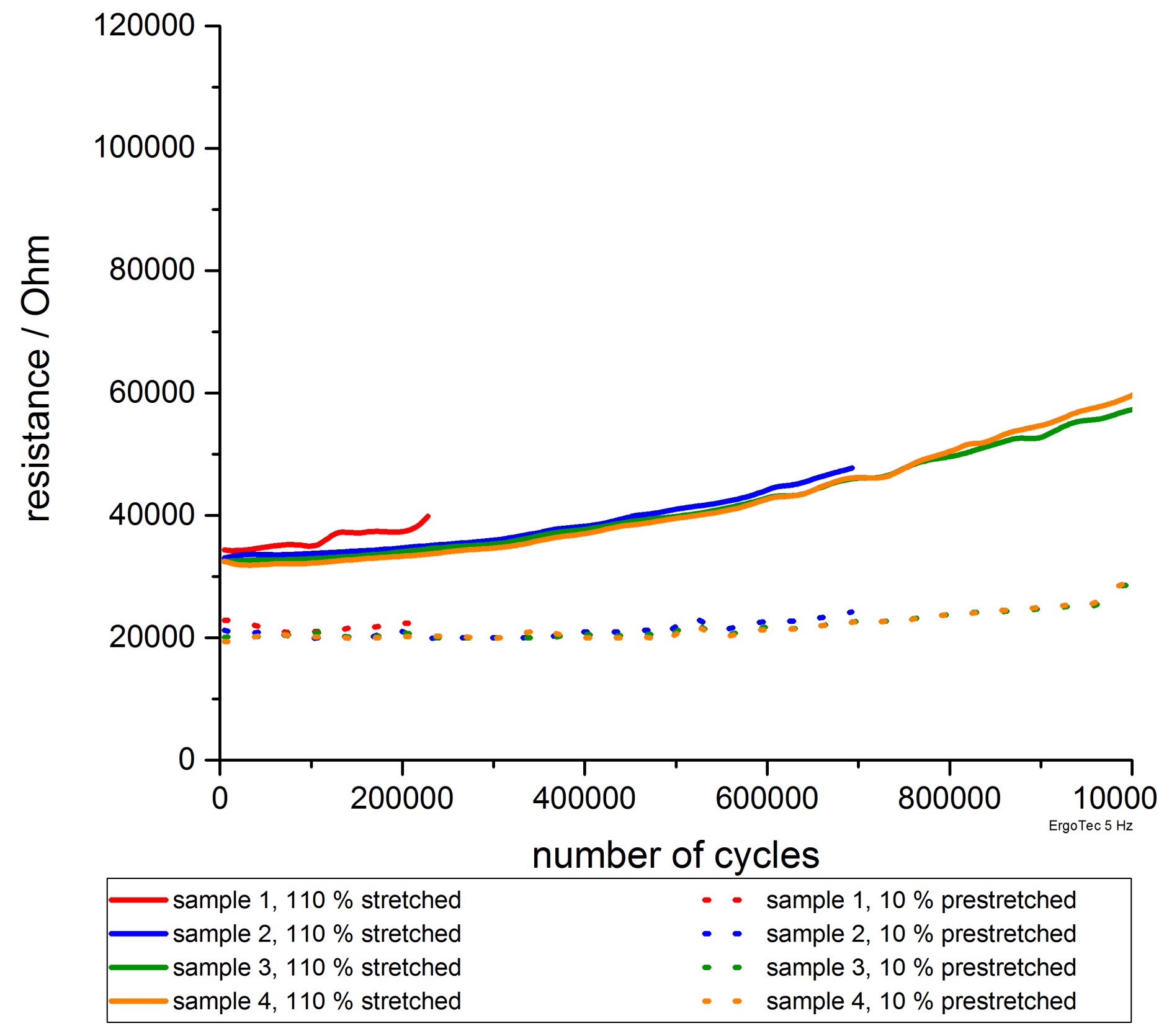

Figure 4: electrical resistance as a function of number of cycles, stretched and unstretched for conductive material D2

Experimental results

Two rubber materials with different crosslinking densities were investigated for the intermediate conductive layer: D1-2 with a low and D2 with a high crosslinking density. A statement about the crosslinking density is made by looking at the Shore A hardness and the loss factor of each material, shown in Table 1. The higher Shore A hardness as well as the lower loss factor indicate an increase in the crosslinking density of D1-2 to D2, independent of using carbon black as filler.

	Shore A inspired by DIN ISO 7619-1		**Loss factor @ f = 5 Hz, γ = 0.1 %**	
Carbon black	without	with	without	with
D1-2	13	27	0.122	0.320
D2	24	42	0.015	0.032

Table 1: mechanical properties of the electrode material D1-2 and D2, with and without carbon black as filler

The dependence of the electrical resistance as a function of the number of cycles is shown in Figure 3 for the material D1-2 and in Figure 4 for the material D2. Each material was tested by using 4 samples, but especially in Figure 4 (material D2) a mechanical failure of the samples 1 and 2 at approx. 200,000 and 700,000 cycles can be seen.

Each figure shows an increase of the resistance depending on the rising number of cycles, but the elastomeric network gets damaged differently. Material D1-2 with low crosslinking density shows an increase of resistance (measured at maximum strain) of nearly 439 %, while the ascent gets calculated by the following equation: $pitch = \frac{R_{cycle\ 1\ Million} - R_{cycle\ 1}}{R_{cycle\ 1}} * 100\%$

Unlike the material with the low crosslinking density, material D2 shows only an increase of resistance of 80 %, shown in Figure 4. Samples 1 and 2 unfortunately do not withstand one million cycles, but they show a similar curve progression till the rupture, so it can be assumed that the curve progression is reproducible.

Conclusion

This investigation shows that the crosslinking density of a conductive silicone rubber material has a strong influence on the behavior of the electrical resistance. Within the mechanical fatigue test material D1-2 shows an increase of resistance of 439 %, while the resistance of material D2 only increases by 80 %. Consequently, a higher crosslinking density has a positive influence on the resistance behavior of an EAP during the lifetime, thus the developed material D2 almost fulfils the requirements of an EAP generator.

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