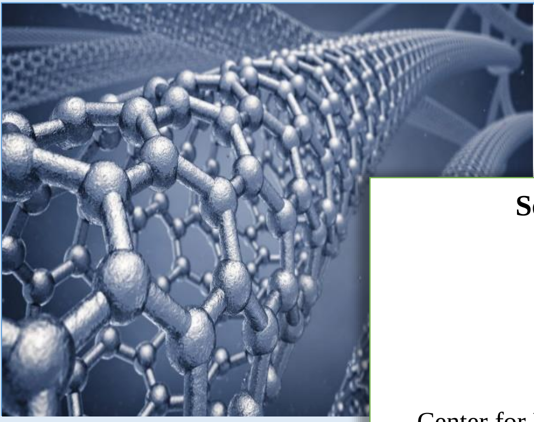

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Separating Curing and Temperature Effects on the Temperature Coefficient of Resistance for a Single-Walled Carbon Nanotube Nanocomposite

Milad Jafarypouria, Biltu Mahato and Sergey G. Abaimov *

Center for Petroleum Science and Engineering, Skolkovo Institute of Science and Technology, Bolshoy Boulevard 30 bld. 1, Moscow 121205, Russia
* Correspondence: s.abaimov@skoltech.ru

Introduction

The temperature coefficient of resistance (TCR) determines the electrical performance of materials in electronics. For a carbon nanotube (CNT) nanocomposite, change of resistivity with temperature depends on changes in CNT intrinsic conductivity, tunnelling thresholds and distances, matrix' coefficient of thermal expansion, and other factors. **In our study, we add one more influencing factor–the degree of cure.** Complexities of the curing process cause difficulties to predict, or even measure, the curing state of the polymer matrix while uncertainty in the degree of cure influences TCR measurements leading to biased values. Here we study the influence of the cure state on the TCR of a single-walled CNT/epoxy polymer nanocomposite. For the given degree of cure, TCR measurements are conducted in the temperature range 25–100 ◦C, followed by the next 24 h of post-curing and a new cycle of measurements, 8 cycles in total. We find that contrary to industry practice to expect a high degree of cure after 3 h at 130 ◦C, the curing process is far from reaching the steady state of the material and continues at least for the next 72 h at 120 ◦C, as we observe by changes in the material electrical resistivity. If TCR measurements are conducted in this period, we find them significantly influenced by the post-curing process continuing in parallel, leading in particular to non-monotonic temperature dependence and the appearance of negative values. The unbiased TCR values we observe only when the material reaches the steady state are no longer influenced by the heat input. The dependence becomes steady, monotonically increasing from near zero value at room temperature to 0.001 1/◦C at 100 ◦C.

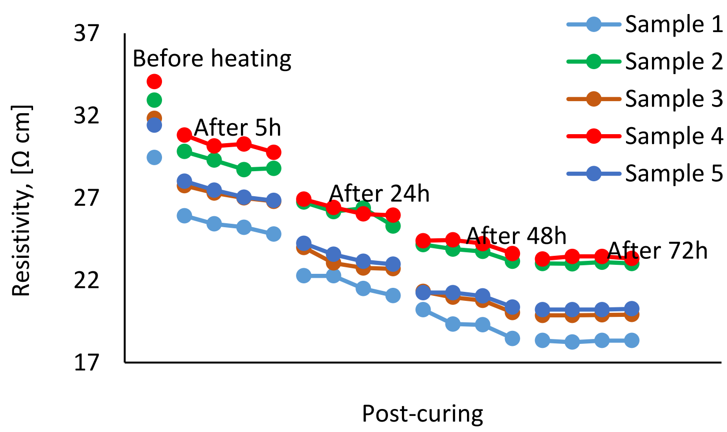
Materials and Methods

SWCNT masterbatch TUBALL™ MATRIX 201 (OCSiAl) was mixed with Biresin CR131 resin by shear mixing for desired 0.6 wt.% of CNTs at room temperature of 25 ◦C and relative humidity of 30%. The low vacuum of 0.1 mbar was applied for 15 min between each stirring cycle to reduce air entrapment.

Results and Discussion

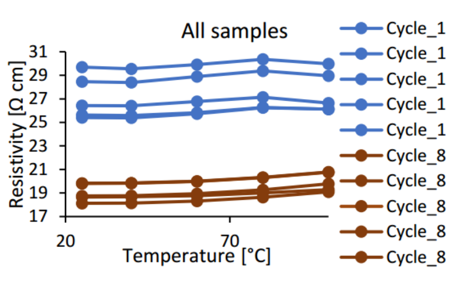
Electrical Resistivity Change during Uninterrupted Post-Curing:

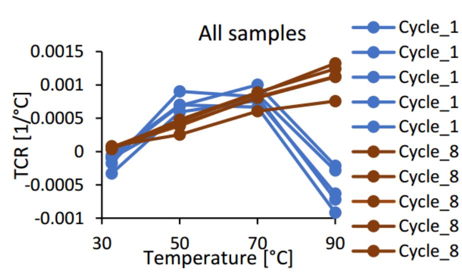
For the five samples, uninterruptedly post-cured at 120 ◦C for 72 h. The decreasing trend is clearly observed, indicating the continuation of the curing process. We argue that the way the samples were manufactured (industrial curing at 130 ◦C for 3 h) does not allow them to reach a high enough degree of cure since post-curing clearly changes material properties.



Changes in Electrical Resistivity with Temperature at Different Post-Curing States:

The dependence of the electrical resistance on temperature for the CNT/epoxy nanocomposite was investigated within 8 thermal cycles, each providing 24-h post-curing at 100 ◦C, interrupted for measurements. Clearly, three trends can be observed: (1) the resistance decreases with post-curing until the material reaches the fully cured steady state (cycles 7 and 8); in cycles 1 and 2 the increase in resistance with temperature is not monotonic, exhibiting a peak, leading to the appearance of negative TCRs at higher temperatures; (3) in the fully cured state (cycles 7 and 8) the increase in resistance with temperature is monotonic, demonstrating only positive TCRs.





Conclusion

- **Industrial curing at 130 ◦C for 3 h does not allow them to reach a high enough degree of cure.**
- **In the fully cured state, the material demonstrates stable, monotonically increasing dependence of TCR on temperature.**