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# Prototyping a Conductive Polymer Steering Pad for Rail Freight Service

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## ABSTRACT

*The AdapterPlus$^{TM}$ steering pad is a polymer component on a railcar that helps to reduce stresses on the axle as a railcar rounds a curve. One railway application requires a minimum of 240 mA to be passed through the steering pad to the rail, which activates air valves that control automated cargo gates. Currently, two copper studs are inserted into the pad to provide a conductive path. However, after continuous cyclic loading caused by normal service operation, the copper studs deform, wear, and eventually lose contact between the two surfaces rendering the pad nonconductive. One proposed solution to this problem is to create a steering pad made entirely from an electrically conductive material. The University Transportation Center for Railway Safety (UTCRS) research team has successfully created a conductive nanocomposite made from vapor grown carbon nanofibers (CNFs) and a modified form of Elastollan 1195A thermoplastic polyurethane (TPU). Previous attempts to create this material were promising but failed to produce an electrically conductive specimen when injection molded. Preliminary results have shown that the new material can be injection molded to create an electrically conductive test specimen.*

*An injection molded insert was designed, fabricated, and incorporated into the existing steering pad design for further testing. Pressure measurement film had previously been used to find the points of maximum stress inside the pad to optimize the design of the composite insert. Characterization of the resistivity of the composite material was carried out in order to verify functionality in future iterations of this product. The resistance of the composite material is expected to be non-linear with a strong dependence on load and voltage. Conductivity tests were performed using a material testing system with a compressive load ranging from 1500 pounds to 5500 pounds. The voltage at each load was also varied between 10V to 20V and the non-linear resistance of the material was examined. The results have shown that the CNF/TPU composite is a potential replacement for the current TPU used for the pad and, with minimal modifications, can be implemented in field service operation.*

## INTRODUCTION

Carbon nanofibers (CNFs) are cylindrical shaped structures created by arranging layers of graphene as stacked cups. CNFs exhibit excellent mechanical properties, high electrical conductivity, and high thermal conductivity. They have extremely high length to diameter ratios, as well as surface area to volume ratio [1]. Because the CNFs have such small volumes, they can be compounded into a polymer matrix and not drastically stress the polymer backbone, which helps to maintain the mechanical properties of the matrix and therefore allow for efficient load transfer between matrix and fibers [2]. The mechanical, electrical, and thermal properties of CNFs can be customized through various post production techniques. The CNFs used in this research were heat treated and functionalized with short range ordered structures to increase the fiber electrical conductivity [1, 2].

Thermoplastic Polyurethane (TPU) is a block copolymer with alternating portions of soft segments, and hard segments [3]. The soft segments of TPU are long and flexible and account for most of the viscoelastic properties of the material. Under proper processing conditions, the hard segments of the polymer can form crystals, which cause phase separation between the two different segments. This creation of two distinct phases leads to both high strength due to crystallinity and pinning effect of the hard segments, and good toughness from the soft segments [4].

Conductive polymer composites are great for electromagnetic interference (EMI) shielding and electrostatic discharge protection. Alternatives to carbon fiber fillers are carbon black and metal fibers. However, compared to carbon nanofiber composites, the metal fiber composites are much heavier and are more difficult to recycle. Carbon black composites require a significantly high concentration of carbon black to create a conductive material. This high concentration of carbon black often results in a material with low toughness and low wear resistance [2, 5].

Carbon nanofibers (CNF) provide conductivity either through direct contact and/or tunneling. As the name suggests, in direct contact, the fibers in the matrix are physically touching end to end forming fiber chains throughout the matrix. The disadvantage of direct contact is that the networks developed can cause agglomerates in the polymer matrix that act as stress risers. Tunneling on the other hand, consists of a CNF network where the fibers are within 10nm of each other. At this distance, electrons being transmitted along the fibers can "jump" from fiber to fiber. Achieving a tunneling effect in the matrix requires more fibers and more mixing that makes the composite more expensive. However, the mechanical properties of a conductive composite made in this way are significantly better [2, 6].

The adapter pad plus steering pad, shown in Figure 1, is a polymer component of a rail car that helps to reduce stress on the axle as a railcar rounds a curve. The pad is composed of TPU due to the polymer's elasticity and durability. Two copper studs are inserted into the steering pad to allow for the transfer of electronic signals that allow for owners to communicate back and forth with their railcars. However, over time, as the car experiences cyclic loading and unloading, and shear stress from the shifting load, the copper studs in the pad wear and may eventually loose contact. The proposed solution is to create a homogenous conductive pad using a CNF/TPU composite material.

*Figure 1: Adapter Plus Steering Pad*

## EXPERIMENTAL SETUP & PROCEDURES

Previous studies have shown that the portion of the steering pad that carries the most load was at the interlocks. For this reason, it was decided to create the conductive inserts with the same profile as the interlocks to ensure that the conductive portion of the prototype pad was constantly under load. The mold was created by taking the profile of the bottom portion of the adapter pad plus system and making a computer numerical control (CNC) path. The mold is shown in Figure 2.

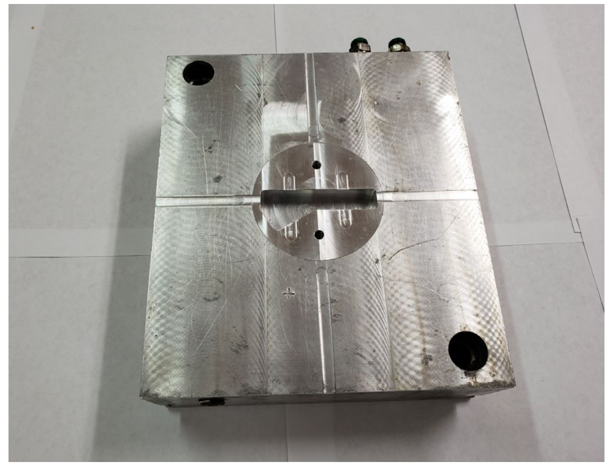

*Figure 2: Aluminum mold used to make conductive inserts*

Currently, the adapter steering pad is molded using a TPU polymer. In order to match the existing pads mechanical behavior, a different TPU was chosen so that the composite behavior of the CNF closely resembles the behavior of the commercial pad [2]. The composite material used in the experiments is a blend of 15% CNFs and 85% TPU, by weight. The TPU used in these experiments was a modified version of Ellastollan 1195A provided by BASF. The modification results in a polymer which "crystallizes" more rapidly than the standard material. TPU pseudo-crystals are formed by association of the hard segments in the polymer chain and the total degree of crystallization is still relatively low. The carbon nanofibers used were Pyrograf-III PR-19-XT-LHT. The two materials were blended and pelletized by Applied Sciences Inc., using a proprietary procedure which produces a blend with maximum conductivity.

Prior to molding, the composite material was dried in an oven for four hours at 230°F to ensure parts were free of defects. Test parts were made using a Boy injection molding machine. The mold was held at a constant 120°F throughout the molding process by means of a heated water circulation system. The highest recommended molding temperatures were chosen to minimize shear stresses in the melt to reduce the risk of fiber breakage. High mold temperature has also been found to be critical to the full development of pseudo-crystals in the TPU which maximize conductivity. The nozzle of the injection molding machine was set to 440°F and the remaining four zones were set to 420°F. The injection molded parts were held in the mold for 90 seconds before being removed and allowed to cool to room temperature. The parts were then epoxied together with a polyurethane compatible adhesive (JB Plastic Bonder) and bonded side by side. The bonding was done primarily to facilitate handling and installation of the parts and is not necessary during pad loading. Throughout the curing phase, excess squeezed out adhesive was scraped off the top and bottom surfaces of the inserts to ensure that adhesive did not interfere with the conductivity of the parts. The relevant section of a standard TPU pad was removed by milling and the assembled inserts were then bonded into the pad. The final prototype pad with conductive insert is pictured in Figure 3.

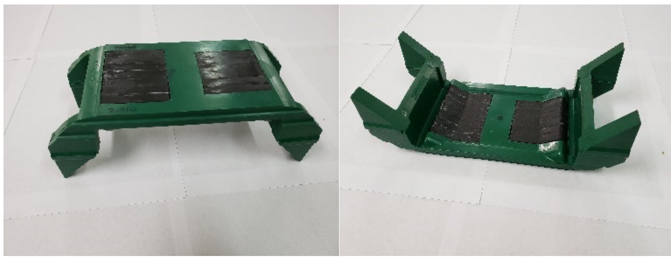

*Figure 3: Prototype Steering Pad with Conductive inserts at Interlocks*

The experiments were performed on a servohydraulic material testing System (MTS 810) under compressive loads of 1500 pounds, 3500 pounds and 5500 pounds. The final 5500-pound load corresponds closely to the 5800-pound load that is seen by a single class F and K bearing at 17% load, which corresponds to the weight of an empty railcar. The scenario of a fully loaded car was not explored in this study because initial results have shown that the conductivity of the material typically increases with increasing load. Therefore, the proverbial "worst case scenario" for the prototype pad is at the 17% loading condition. Then, a potential difference of 10, 15, and 20 volts was applied across the pad. Although 24 volts is the typical potential difference applied to the system, 20 volts was chosen as the final testing voltage to account for any inefficiencies in the power source and potential losses that may be seen in actual use. In order to simulate the prototype pad on an actual railcar, a bearing substitute was created by cutting the outer ring (cup) of a class F bearing in half and welding a ¼" plate to the bottom half of the ring. Then, half circle supports were added to the front and rear faces of the bearing. A piece of sheet metal was then placed on the top face of the pad to apply the desired voltage to the system. The simulated bearing assembly including prototype pad and adapter was then placed between two ½" thick polymer sheets to ensure that the test stack was electrically isolated from the testing machine. Lastly, an I-beam was placed on the top polymer sheet to distribute the load across the pad. The final setup, minus the I-beam, is shown in Figure 4.

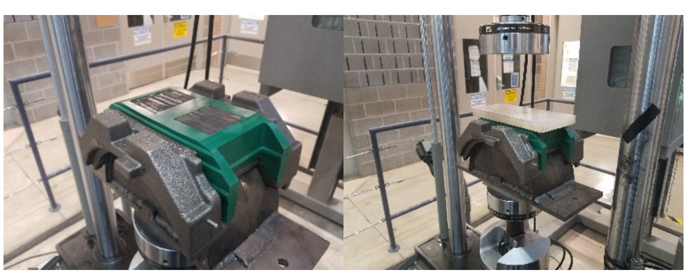

*Figure 4: Prototype Polymer adapter steering pad on simulated bearing in material testing system*

For each test, the voltage of the system was supplied one second after the load was applied. Between each test, the prototype pad was completely unloaded, electrically grounded, and allowed to rest for one hour in order to negate the effects of any previous test.

A National Instruments (NI) USB-6008 data acquisition system (DAQ) programmed using LabVIEW™ was utilized to record and collect all the data for this study.

## LABORATORY RESULTS

In practice, the steering pad must be able to actuate a solenoid valve at 20 volts while carrying an unloaded car. In short, in order to consider the prototype pad a success, the pad must have a resistance of no more than 14 ohms when 20 volts and 5500 pounds are applied to it. This desired resistance is plotted in each of the charts for comparison.

Figure 5 illustrates how the resistance of the pad changes over time under various load conditions at a 10-volt potential difference. As expected, the electrical resistance of the prototype pad decreased as the load increased from 1500 pounds to 3500 pounds. This is because as the material is compressed, the carbon nanofiber networks between the polymer chains move closer to each other making it easier for electrons to pass through the network. The effect of load on the resistance appears to diminish somewhere between 3500 pounds and 5500 pounds. In fact, Figure 6 shows that the average steady state resistance at 3500 pounds, 14.7 ohms, is slightly less than the average steady state resistance at 5500 pounds, 15.0 ohms. This observed difference is most likely due to variation in contact resistance between the pad and fixture due to repositioning or prior loading history.

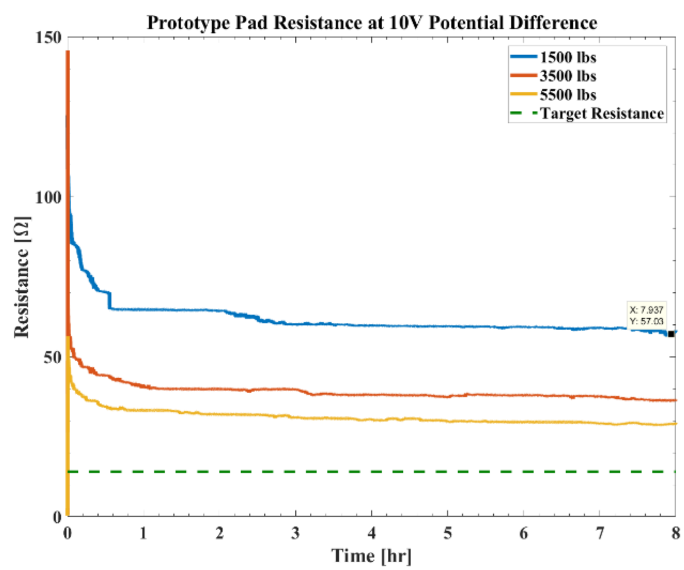


*Figure 5: Prototype Pad with 10-volt potential difference with various applied loads*

Another parameter analyzed in the experiments was the composite conductivity dependence on voltage. It can be seen from Figure 7 that after 8 hours with a 1500-pound load and 10-volt potential difference applied to the system, the average steady state resistance of the material was approximately 58.9 ohms, while with a 20-volt potential difference, the resistance of the prototype pad was about 26.4 ohms. This trend is also seen at loads of 3500 pounds and 5500 pounds as presented in Figure 8 and Figure 9, respectively.

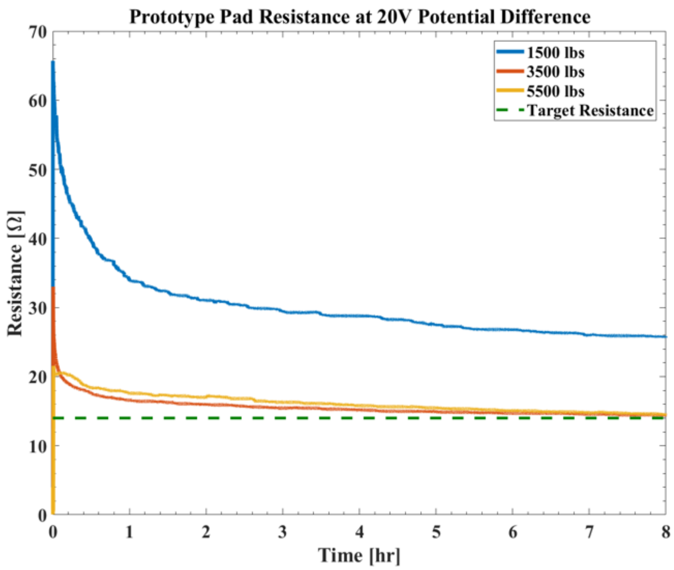


*Figure 6: Prototype Pad with 20-volt potential difference with various applied loads*

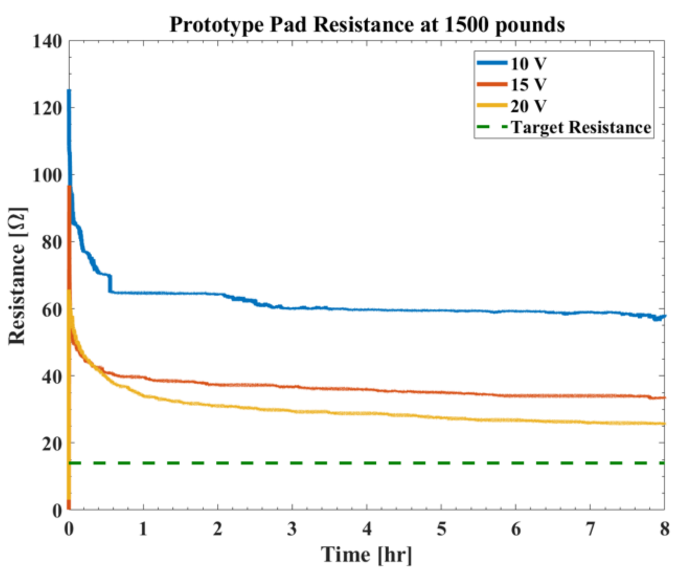


*Figure 7: Prototype pad resistance at 1500 pounds and various potential difference*

The transient response is shown in these experiments mainly for academic purposes. It is interesting to note that the initial resistance of the pad when it is first loaded can be nearly twice the steady-state value. Depending on the loading and voltage conditions, the settling time can vary from as little as 0.6 hours to nearly 1.5 hours. However, in practice, the pad will only see a zero load if the railcar itself is removed from the wheel-axle assembly so settling time will not be a factor in actual service.

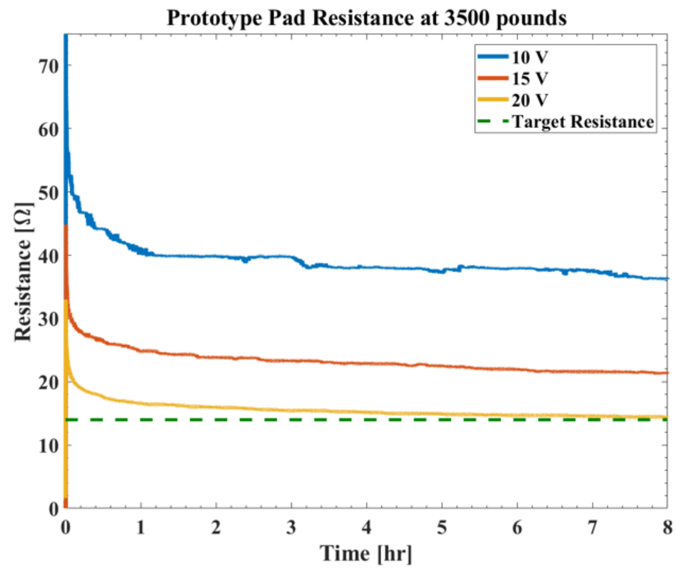


*Figure 8: Prototype pad resistance at 3500 pounds and various potential difference*

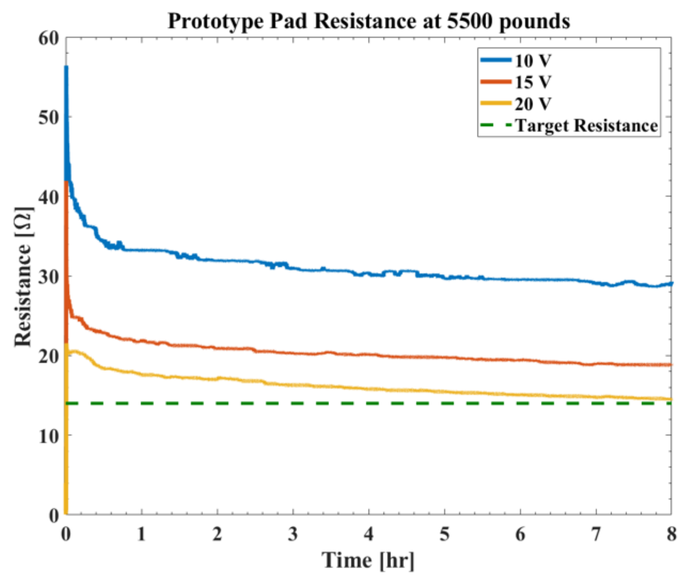


*Figure 9: Prototype pad resistance at 5500 pounds and various potential difference*

The average steady state resistance for all conditions analyzed is given in Table 1. These values are the average resistance of the system from hours five to eight for all the tested scenarios. It can be seen from the table that the prototype pad had a resistance that was 1 ohm higher than the 14 ohms required for valve actuation when tested at 5500 pounds and 20-volt potential difference. Since actual service loads and voltages are higher than these values (5800 lbs and 24 volts respectively), this is unlikely to be a problem. In addition, replacing more of the pad with conductive TPU would increase the conductive area thus reducing resistance proportionate to the increase in area.

*Table 1: Steady State Resistance under various Voltage and Loading Conditions*

| Steady State Resistance [Ω] | | Applied Voltage [V] | | |
|---|---|---|---|---|
| | | 10 | 15 | 20 |
| Load [lb] | 1500 | 58.9 | 34.1 | 26.4 |
| | 3500 | 37.5 | 21.8 | 14.7 |
| | 5500 | 29.4 | 19.2 | 15.0 |

## CONCLUSIONS

The study analyzed the effect of load and applied potential difference on the resistance of a prototype adapter steering pad. The prototype pad was created by removing a section of the actual steering pad and inserting an injection molded part made of a blend of 15 weight percent carbon nanofibers and 85 weight percent TPU. The tests show that between 0 and 3500 pounds of applied load, the resistance of the pad decreases as the applied load on the pad increases. Above 3500 pounds, increasing load appears to have no further effect on resistivity. Also analyzed in this study was the effect of voltage on the resistivity of the material. It was shown that the resistance has a non-linear dependence on the voltage, specifically, as the applied potential difference increases, the resistance of the material decreases.

Future work planned for the prototype includes testing the system under cyclic, or vibrating loads, as experienced in actual operation. It is believed that conductivity of the composite is related to the crystallinity of the polymer matrix since control of crystallization or hard section ordering in the TPU has been shown to be critical to achieving the desired conductivity. Further work into this relationship is planned to characterize the interaction of crystallization and conductive network formation to better guide process optimization and future resin development. Finally, resistance measurements will also be performed at a range of temperatures consistent with rail operations.

## ACKNOWLEDGEMENTS

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