

NEW ADVANCES IN PRIMERLESS SILICONE INSULATION MATERIALS

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Abstract: Silicone rubber laminate insulation materials have a long history of successful service in diesel-electric locomotive traction motors dating back to the 1950's. Silicone rubber is an excellent material choice for this application because of its outstanding thermal stability, good electrical insulation properties, consistent flexibility, and tenacious bond strength. However, the process for applying silicone rubber laminate insulation tape requires a cumbersome priming step. Recent advances in silicone compound chemistry have led to the formulation of primerless silicones that bond without the priming step. Using primerless silicone rubber laminate insulation tape leads to a more robust application process, as well as improved material properties such as adhesion strength, dielectric strength, volume resistivity, and thermal stability. This paper presents the results of a comparative study conducted on primerless and conventional silicone rubber laminate insulation tape, demonstrating the technical advantages of primerless technology.

Key Words: Primerless, Traction Motor Tape, Silicone, Thermal Stability, Elastomer, High Temperature, Low Temperature, Adhesive, Electrical Insulation

I. INTRODUCTION

Silicone impregnated woven fiberglass fabric tape, Traction Motor Tape (TMT), is routinely used to insulate high voltage copper conductor coils of stator electromagnets in direct current (DC) locomotive traction motors. By chemically adhering to the field coils, silicone TMT provides robust high voltage electrical insulation in a wide range of demanding environmental conditions. The application and processing method for insulating DC traction motor electromagnets is a well-established and effective manufacturing process. However, recent advances in silicone compound chemistry and TMT composite construction simplify this manufacturing process while producing electrical insulation with superior performance. The development of TMT using primerless silicone chemistry eliminates several manufacturing steps, leading to reduced manufacturing cycle time. Primerless silicone TMTs eliminate the negative aspects of employee and environmental exposure to prime coats containing hazardous volatile organic compounds. Lastly, new

silicone chemistry is used to create a new composite insulation material that has better and more stable physical and electrical properties than current insulation technology.



Figure 1 -Main field coil from a DC traction motor wrapped with silicone Traction Motor Tape.



Figure 2 - Interpole coil from a CD traction motor wrapped with silicone TMT

The conventional TMT insulation application process has several steps. First, the copper conductor surfaces are abraded to remove oxides and contaminants and increase surface energy. The surface is subsequently cleaned with an alcohol solvent to prepare for the prime coat step. The prime coat step is necessary so that the silicone TMT can be chemically coupled to the copper conductor surface. The prime coat usually consists of a silane coupling agent

system dispersed in a solvent carrier. A thin layer of primer is applied to the copper conductor. The control of primer quantity is critical, because both underpriming and overpriming can lead to poor TMT adhesion. The primed conductor must stand for a significant dwell time prior to TMT application to allow solvent flash and initiation of coupling kinetics. The silicone TMT is then applied by hand or in an automated process utilizing tape reels for coil radii and sheet goods for coil faces. The wrapped coil is then placed in laminating equipment where heat and pressure are applied to chemically crosslink and couple the silicone TMT insulation to the copper conductor surface. Lastly, the coil is post-baked in order to complete the coupling process, remove organic peroxide by-products used to initiate silicone crosslinking, and stabilize the silicone matrix by removal of low molecular weight siloxanes.

Utilization of primerless silicone chemistry allows for the elimination of the priming process to couple the silicone TMT to the copper conductors. As a result, cycle time is reduced significantly. An additional benefit is that the chance for defectively primed coils is eliminated. Using conventional silicone TMT, defects can form as blisters and delamination at the silicone TMT and copper conductor interface, often requiring subsequent repair steps or even complete insulation rework.

Traditional silane primer chemistry presents personnel exposure and environmental impact issues that must be managed. Hazardous conditions are managed by regulatory personnel to ensure employee safety and environmental compliance. However, industrial hazards can be mitigated and even eliminated through new technologies such as primerless silicone TMT. Because prime coat materials are eliminated with primerless technology, the volatile organic compounds used as solvent carriers are also eliminated. While solvent carrier types can differ given the variety of commercial grade prime coat materials, in general they are highly flammable liquids with extremely low flash points. Additionally, these solvent carriers can cause skin, eye, and respiratory irritation through acute toxicity and possibly major organ damage through chronic exposure if not carefully managed. Industrial management and regulation of these carrier materials is required through OSHA and local governing bodies. Oversight of these hazardous components in today's electromagnetic coil insulation processes is no longer necessary because solvent carrier functionality has been eliminated with primerless silicone.

Besides process simplification and reduction of hazardous components, primerless silicone TMT technology also leads to an improvement in electrical insulation on many fronts. Key properties for silicone TMT insulation

include excellent adhesion strength to copper conductor surfaces, high voltage dielectric breakdown strength, excellent volume resistivity, and stability of these properties when subjected to elevated operating temperatures and hostile environmental conditions. Adhesive strength of the silicone TMT to the copper conductor during traction motor operation is paramount because insulation delamination can lead to voltage arcing and potential insulation damage. High dielectric breakdown strength is necessary to ensure that the electromagnetic coil's conductive path is maintained so that motor power and longevity are assured and maintained. High volume resistivity assures that leakage currents, especially those induced by contamination and moisture, are mitigated. Lastly, these specific properties must be maintained over thousands of hours of high temperature motor operation where thermal/mechanical load from both thermal cycling and dynamic vibration encountered in mobile motors strain electrical insulation systems. Primerless silicone technology coupled with a highly electrically insulative fiberglass fabric weave configuration produces a superior TMT compared to that of conventional TMT material in all property categories. The key to the technological improvement is the stability of these properties versus conventional technology after thermal stress. Stability is anchored by the silicone's ability to resist depolymerization (intermolecular and intramolecular chain scission) and oxidative embrittlement. Primerless silicone offers superior resistance to both thermal degradation mechanisms to ensure that key material requirements remain intact over the motor service life.

II. DISCUSSION

A. Manufacturing cycle time reduction and defect reduction

The use of Primerless TMT tape versus Conventional tape offers the elimination of major steps in the electromagnet coil insulation manufacturing process. The targeted step for elimination is the copper conductor prime coat application step.

Priming copper conductor surfaces with a commercial grade primer is necessary to adhere conventional TMT insulation materials. The prime coat is generally an organosilane coupling agent dispersed in an alcohol or hydrocarbon solvent. The silane's general molecular structure is an organofunctional group and three alkoxy hydrolyzable groups configured around a silicon atom. The commercial grade silanes are generally applied to the copper conductors via brush application but can also be applied by spray or dip. Once the primer is applied the organosilane undergoes four steps so that a coupling layer between the organic pendant groups of the silicone

polymer and the hydroxyl groups of the copper conductor surface can be chemically adhered.

Step 1: The alkoxy groups hydrolyze via surface moisture and atmospheric moisture as the solvent carrier evaporates

Step 2: Condensation into small oligomers occurs

Step 3: The small oligomers form hydrogen bonds with the hydroxyl groups of the copper substrate.

Step 4: Covalent bond formation occurs between the organofunctional reactive group of the organosilane and the silicone organic pendant group and between the hydrolyzed groups of the organosilane and the copper surface to couple the silicone to the copper [1] (See Figure 3)

Primerless silicone technology eliminates steps 1 through 4 from the application process. The coil surfaces can be simply cleaned, wrapped with primerless TMT insulation, vulcanized under pressure at elevated temperatures, and then post-cured. The priming step is completely avoided for faster product throughput.

Removing the priming step in the application process of silicone TMT application also creates a more robust manufacturing process by eliminating potential for defects caused by over and under priming. Most commercial grade primers are applied in a very thin layer so that a molecular layer of coupling agent remains on the copper conductor surface after the carrier evaporates. Because the dried primers are difficult to see, there is a chance that the copper conductor surface will be underprimed, which ultimately leads to delamination of the TMT insulation. However, most problems with silane priming occur from overpriming. When a copper conductor surface has been overprimed the coupling agent tends to pool and accelerated condensation occurs. Overprimed surfaces usually have a cloudy appearance to them because the organosilane has started to precipitate. In this scenario, the prime coat will not bond effectively as the condensed oligomers are not adhered well to the copper substrate once again leading to possible delamination of TMT insulation.

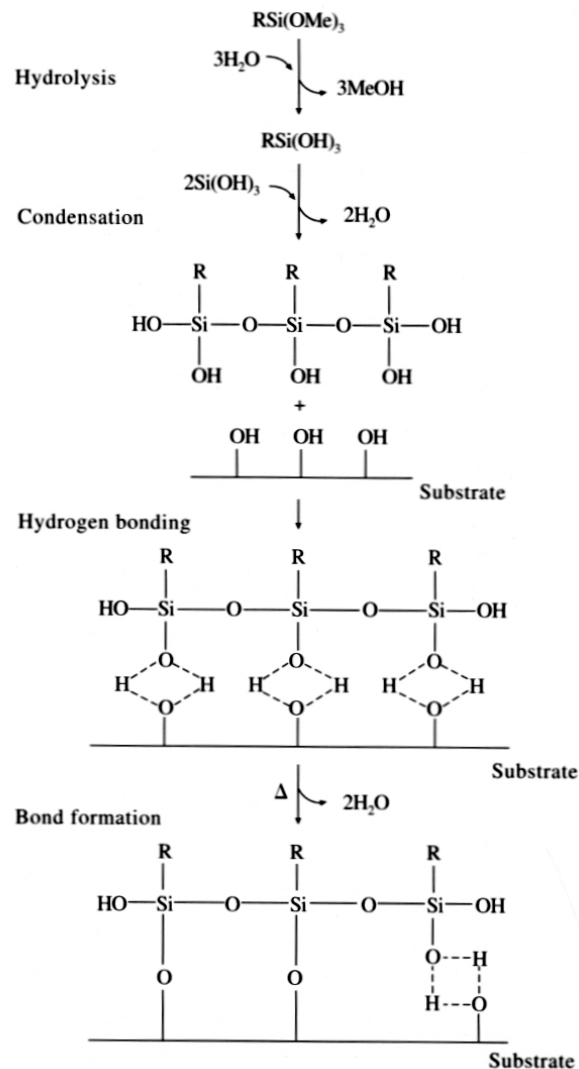


Figure 3 [2]

Not all copper conductor surface prime coats are organosilanes, but even with non-silane commercial grade prime coats it is difficult to guarantee prime coat consistency from operator to operator.

B. Employee and Environmental Safety Improvements

Health and safety of operators are a principal priorities in manufacturing along with environmental stewardship. The carriers or the volatile organic content for organosilane prime coats and even non-silane prime coats must be monitored for employee safety. Most carriers present a fire hazard as they have low flash points well below room temperature coupled with high flammability.

OSHA also regulates employee exposure to hazardous volatile organic compounds such as methanol and naphtha. The permissible exposure limits (PEL) as a time

weighted average for exposure is 200 ppm and 500 ppm respectively for these commonly used prime coat carriers. [3] Adequate exhaust is recommended for both materials to keep airborne concentrations below the PEL. Both carriers may also cause skin, eye, respiratory, and digestive tract irritation through acute exposure. Chronic or high level exposure to methanol may lead to kidney, eye, and central nervous system damage while chronic exposure to naphtha may lead to dermatitis and central nervous system depression. [4,5] Lastly, local government agencies may regulate fugitive release of these volatile organic compounds.

C. Comparative Analysis (Primerless TMT vs. Conventional TMT)

1. Initial Key Properties

The following table compares Primerless and conventional silicone traction motor tape insulation, clearly demonstrating adhesion and volume resistivity advantages for primerless TMT.

Property	Primerless	Conventional
Dielectric Breakdown Strength	788 VPM	838 VPM
S1 to S2 Adhesion Strength	10.9 ppiw	6.2 ppiw
S2 to Copper Adhesion Strength	10.7 ppiw	5.7 ppiw
Insulated Interpole Volume Resistivity	>50 GΩ	13.5 MΩ

Table 1

Dielectric breakdown specimens were prepared in a heated platen press under 50 psi and then post cured for two hours at 204°C in a mechanically circulated oven. The specimens were tested for dielectric breakdown strength according to Arlon's SQA-TMS-020 work instruction. This work instruction references ASTM D149, which covers dielectric breakdown voltage and electric strength of solid electrical insulation materials at commercial power frequencies.

The Side 1 to Side 2 (S1 to S2) adhesive strength coupon specimens were prepared to represent the over-wrapping of TMT during insulation of electromagnet copper coils. Test samples were prepared in a heated platen press under 50 psi of lamination pressure according to Arlon's SQA-TMS-011 work instruction. The test pull rate was 2"/minute. This work instruction references ASTM D1876, which covers peel resistance of adhesives (T-peel test). The specimens were additionally post-cured for two hours at 204°C in a mechanically circulated oven before adhesion strength was measured.

The S2 to copper adhesion strength coupons were also evaluated in a similar manner. However, for the Conventional TMT to copper specimens, the copper surface was initially abraded with a scotchbrite pad, cleaned with Isopropyl Alcohol (IPA), and then primed with a 2:1 volumetric ratio of IPA:Chemlok 607 primer and allowed to dry for 30 minutes at 50% RH at 23°C.

The volume resistivity was determined by a novel wet high potential test using an insulated DC traction motor interpole electromagnet copper coil. Coils wrapped with Primerless TMT were unprimed and coils wrapped with Conventional TMT were primed for adhesion. The radius area of each coil was wrapped with one-inch wide tape and the straight sections used two layers of wider roll stock. Coils were then wrapped with polyester film for cleanliness and minor abrasion protection. The coils were inserted into the vulcanization fixture and laminated under pressure and inductive heating. The laminated coils were subsequently post cured to stabilize the TMT insulation. The coils were inserted into a water bath and a 5000 volt potential was applied to the copper conductor. The electrical resistance through the TMT insulation was measured.

The initial key property comparison presents a quick look at the two TMT materials. The materials offer similar dielectric breakdown strength and the primerless silicone compound exhibits much stronger adhesion properties. The high volume resistivity performance of the primerless TMT is attributed to the excellent copper to silicone adhesion and the quality composite structure of the silicone impregnated fiberglass fabric of the primerless TMT material.

2. Reversion Resistance – theoretical understanding of key property degradation resulting from silicone depolymerization.

Both the primerless and the conventional TMT compounds were tested for reversion resistance in a Monsanto R-100 Rheometer per Arlon's SQA-TMS-030 Work Instruction. Uncured rubber compound samples were placed in the Rheometer at 204°C and monitored for polymer reversion over a two hour period. The degree of reversion is determined by the percentage change in rheometer torque over a two hour test period from the maximum torque value achieved in that same two hour test period. Polymer reversion is measured and correlated to a percent loss of Rheometer torque.

Rheometer Reversion Resistance	
Compound	Percent torque change from maximum torque
Primerless TMT compound	+ 5.4%
Conventional TMT compound	- 61.0 %

Table 2

Reversion of the silicone polymer occurs in the absence of air at elevated temperatures. Reversion results in the depolymerization of high polymer into low molecular weight siloxanes and degradation of all key properties of traction motor insulation. Results of polymer reversion in TMT are insulation delamination and loss of electrical insulating features. Silicone depolymerization occurs as Dvornic explains, ... by either inter- or intra-molecular siloxane redistribution reactions that occur randomly between the siloxane bonds located inside the polymer chains and proceed through the formation of intermediate four-center states yielding volatile cyclic siloxanes.... [6] As indicated, this process leads to random scission of the high polymer and an overall reduction of polymer molecular weight. [7] Depolymerization in the Arlon Reversion Resistance Test method is additionally aggravated by the presence of acidic peroxide by-products remaining in the polymer and is considered a worst case scenario. Dvornic concludes that, ...,the presence of ionic impurities in polysiloxanes may completely ruin one of the most characteristic and desirable properties of these polymers: their high temperature stability, and that is why only well purified samples (without even trace amounts of acidic or basic impurities, including left-over polymerization initiators) should be considered for high temperature applications. [8]

As shown in Table 2 the primerless TMT compound exhibits far superior reversion resistance when compared to the conventional TMT compound. Polymer reversion is a well-known degradation process that can lead to TMT insulation delamination and loss of electrical insulating functionality. Excellent reversion resistance leads to stability of in-service traction motor insulation in terms of all of the key properties because the silicone polymer is resistant to this type of thermal degradation.

3. Thermo-oxidative stability – key property degradation resulting from silicone oxidation.

a. Dielectric Breakdown Strength Stability

The other component of polymer stability under long term thermal load is the degree of thermo-oxidative resistance. Thermo-oxidative degradation is a result of polymer exposure to air or oxygen at elevated temperatures. During TMT in-service exposure to air at high operational

temperatures, atmospheric oxygen has a natural tendency to bond with silicon atoms to form silica. [9] The thermo-oxidative degradation process of silicone is a slow process, beginning with damage to the polymer through stripping of pendant groups and eventually leading to the onset of excessive polymer chain crosslinking coupled with the formation of pure silica. [10] This degradation process can translate into a loss of polymer flexibility which leads to the onset of insulation micro-cracking, especially when subjected to vibration or thermal/mechanical load. Dvornic summarizes, “When used in air, polysiloxanes normally retain their flexibility for thousands of hours at temperatures of up to about 200°C, or for several hours at 220°C. The loss of flexibility marks the onset of cross-linking reactions, which prevents or greatly reduce the loss in polymer molecular weight and formation of volatile degradation products at these temperatures. Hence, in contrast to many organic counterparts, polysiloxanes do not abruptly deteriorate at elevated temperatures in air, but instead they undergo a gradual reduction of mechanical properties over a period of time.” [11]

In an effort to compare the thermo-oxidative stability of primerless TMT to conventional TMT, the silicone impregnated woven fabrics were subjected to several short term accelerated thermal aging periods with dielectric breakdown as the response. The specimens were prepared as in, C. *Comparative Analysis (Primerless TMT vs. Conventional TMT)* 1. *Initial Key Properties*, and then subjected to the following short term thermal aging periods: 1. 48 hours at 320°C; 2. 96 hours at 300°C; 3. 168 hours at 275°C; and 4. 336 hours at 250°C. Dielectric Breakdown strength was measured after each thermal aging periods. See results in Figure 2

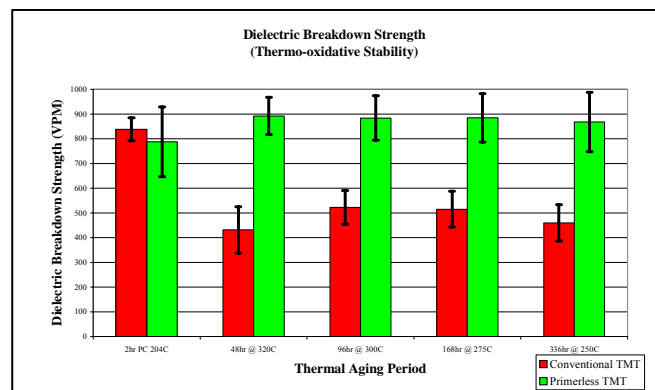


Figure 2

The results clearly demonstrate that aggressive short term thermal cycles cause aggressive crosslinking and micro-cracking of the conventional TMT leading to a near 50% reduction in dielectric breakdown strength for all aging cycles. Comparatively, the primerless TMT shows clear

signs of thermo-oxidative stability in all short term thermal cycles. The primerless TMT does show signs of some excessive crosslinking and loss of elasticity through a slight increase in dielectric breakdown strength after each thermal cycle, but clearly the thermo-oxidative process is retarded and degradation remains in check.

It is noted that short term accelerated thermal aging cycles are a good comparative tool but not indicative of actual in-service material functionality. However, the temperatures chosen are representative of a typical Underwriters Laboratories accelerated aging study for silicones to determine long term estimates of thermo-oxidative stability. Such accelerated tests are generally extended out to 2000 hours to give a more complete picture of material stability in service.

b. S1 to S2 Adhesion Strength Stability

In addition to dielectric breakdown strength, S1 to S2 adhesion strength of both the primerless TMT and a conventional tape were compared after similar short term thermo-oxidative cycles. Adhesion coupon specimens were prepared as in, *C. Comparative Analysis (Primerless TMT vs. Conventional TMT) 1. Initial Key Properties*, and then subjected to the following short term thermal aging periods: 1. 48 hours at 320°C; 2. 96 hours at 300°C; 3. 168 hours at 275°C; and 4. 336 hours at 250°C. Adhesion strength was measured after each thermal cycle. See Results in Figure 3.

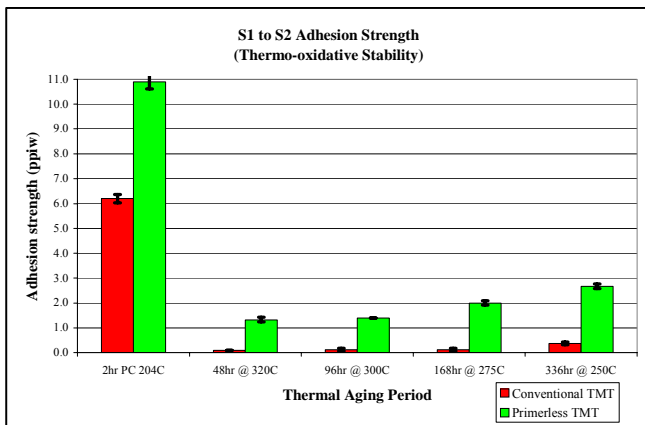


Figure 3

Both the primerless and the conventional TMT bond strength values show dramatic reduction of adhesive strength in each of the elevated thermal cycling periods. This is a clear indication of thermo-oxidative polymer degradation and an obvious loss of polymer elasticity. As expected, the higher temperature cycles produce the greatest amount of adhesion degradation. However, while the conventional TMT adhesion strength appears to show a complete loss in elastic properties required for good

adhesion, the primerless TMT still maintains enough elasticity and subsequent adhesion strength to effectively remain intact as an insulation medium. Advances in silicone chemistry have added thermo-oxidative stability to the primerless TMT compound.

c. S2 to Copper Adhesion Strength Stability

The thermo-oxidative adhesion strength stability comparison of TMT laminated to a copper conductor surface was approached using a unique thermal cycling methodology. The high temperatures in the short term accelerated aging tests tend to produce the formation of Cu₂O, Cu₃O₂, and CuO copper oxide layers on the copper adhesion coupon specimens. The layer readily delaminates from the adhesion coupon specimen rendering comparative T-peel adhesion test results unreliable. So, the TMT tape to copper conductor adhesion strength thermo-oxidative stability was compared utilizing low to high temperature thermal cycling.

The S2 to copper adhesion strength coupon specimens were prepared as in, *C. Comparative Analysis (Primerless TMT vs. Conventional TMT) 1. Initial Key Properties*. Ply adhesion samples were tested for adhesion strength after 25, 50, and 75 thermal shock cycles. One thermal shock cycle is defined as ramping from ~0°C to 204°C in 180 seconds in a mechanically circulating convection oven followed by a 30 second cool down period in ice water to approximately 0°C. This thermal shock cycle not only evaluates potential degradation through thermo-oxidative processes but also evaluates the TMT under thermal/mechanical load induced stress and strain as would be seen in an actual motor ramping to high operating temperatures in a cold field environment.

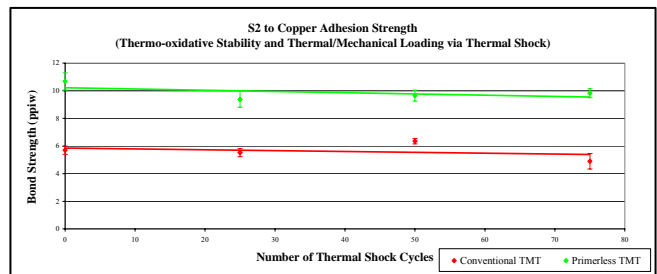


Figure 4

As shown in figure 4, both primerless and conventional silicone TMT materials are able to absorb the thermal/mechanical load and resist thermo-oxidative degradation in this testing method. The adhesion strength of the silicone remains in tact after 75 thermal shock cycles with a negligible loss in S2 to copper adhesion. Primerless TMT retains the S2 to copper adhesion

superiority throughout the testing. This test exemplifies the benefits of silicones as an insulation medium in hostile environments.

III. CONCLUSIONS

Primerless silicone TMT presents a better overall coil insulation solution than conventional silicone TMT. Primerless materials allow the coil assembler to simplify the insulation application process significantly while allowing the elimination of process aids that are hazardous to personnel and the environment. Furthermore, primerless TMT outperforms conventional TMT in key performance areas such as adhesion strength, reversion resistance, and overall thermal stability.

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