RESINATE

No. 3, APRIL 2017

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POWERING MOTOR PERFORMANCE: AN INTRODUCTION TO PEEK EXTRUSIONS

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ABSTRACT

PEEK is a polymer that is a highly versatile and thus popular thermoplastic. As a polarizable dielectric, PEEK has also become popular for its insulating characteristics and is increasingly being explored towards these applications. We at Zeus examined these aspects of PEEK and its potential for applications involving electric motors. We compared motor performance of a readily obtainable 0.75 horsepower, 4-pole, 460 volt, AC induction motor with same motor rebuilt with Zeus PEEK insulated magnet wire and other PEEK insulating products. We found that the motor rebuilt with Zeus PEEK insulated wire performed equal to or better than the OEM motor in nearly every general performance attribute that was tested.

INTRODUCTION TO PEEK POLYMER

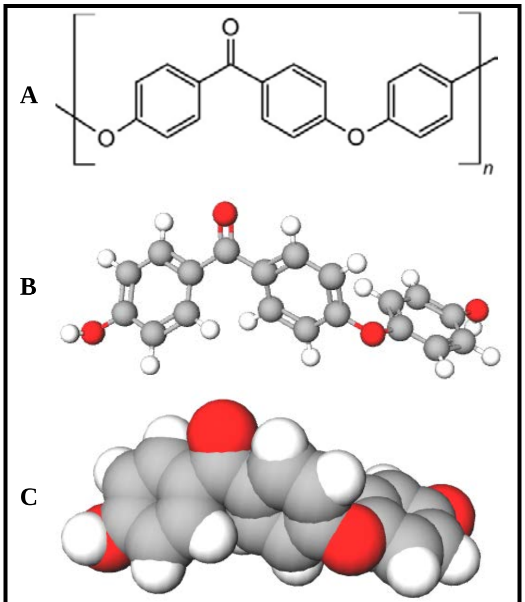

Figure 1: Polyether ether ketone polymer, or [4-(4-methoxyphenoxy)phenyl]-(4-methyl-phenyl)methanone **[1]**. A) Bond-line drawing of the PEEK repeating monomer unit; B) ball-and-stick model and C) van der Waals spheres model showing terminal substituted carbons. White = hydrogen; gray = carbon; red = oxygen. *(Shown with terminal hydroxyls).*

Polyether ether ketone, or PEEK, is a highly popular thermoplastic polymer. This organic compound is part of the family of PAEK (polyaryl ether ketone) polymers which includes other familiar names such as PEK (polyether ketone), and PEKK (polyether ketone ketone). PEEK, like many PAEK family members, is a semi-crystalline polymer at room temperature and is composed of ether and ketone linkages on either side of single aryl moieties (**Fig. 1**). As a thermoplastic, PEEK does not decompose at its melt temperature making it very amenable to melt processing where it can be made into a highly diverse collection of other forms. While the thermoplastic industry has continued to turn out new and ever more specialized plastics, PEEK remains as one of the most important members of this vastly influential group of polymer plastics.

POPULAR PROPERTIES

Although a relative newcomer to the world of thermoplastics (ca. 1978), PEEK has rapidly gained in popularity because of many exceptionally useful properties. Aside from its processability, PEEK is an extremely hard material which translates into high strength and long life for finished products. PEEK's hardness also imparts excellent resistance to abrasion (wear) and galling with a low coefficient of friction. PEEK, like many members of the PAEK family, has relatively low water absorption and is highly unsusceptible to hydrolysis [2, 3]. These attributes contribute to PEEK's extended usage life before embrittlement. Similarly, PEEK is resistant to almost all commonly encountered solvents, detergents, and other chemicals with certain halogenated acids and sulphuric acid being among the few substances that affect it. One of PEEK's most cited properties, however, is its high temperature tolerance where many other similar polymers fail. PEEK melts near 343 °C (649 °F) and has a practical service temperature upper limit of 260 °C (500 °F) with some properties retained above this temperature (**Table 1**). (PEEK's lower temperature limit extends below -70 °C / -94 °F) [4, 5]. Thus, PEEK is one of the most thermally stable polymers. Together, these properties give PEEK extensive possibilities for application across many environments.

Table 1: Representative PEEK properties

Property	*ASTM*	*Value*
Melt temperature (°C / °F)		343 / 649.4
Upper service temperature (°C / °F)		250-60 / 482-500
Low service temperature (°C / °F)		-70 / -94
Glass transition temperature (°C / °F)		150 / 302
Tensile strength (MPa)	D638	75 – 97
Water absorption (%)	D570	0.1 – 0.45
Density (g/cm^3)	D792	1.10 – 1.48
Volume resistivity (Ω · cm)	D257	1.6×10^{16}
Dielectric strength (V/mil)	D149	504
Dielectric constant (@ 1 MHz)	D150	2.2 – 3.0
Color		opaque; light tan or brown

Table 1: PEEK properties shown are for native or unfilled PEEK polymer resin.

VERSATILITY OF PEEK

PEEK is a polymer that has found its way into a multitude of highly specialized and general application fields. As a thermoplastic with exceptional hardness, PEEK can be injection molded into parts such as pipe flanges, engine components, dental implants, structural parts, and even load-bearing parts such as bushings or bearings. PEEK is also very machinable for finer tolerances such as those necessary for screws or other threaded parts. PEEK can be extruded to form a broad spectrum of radial parts including gears, joint seats, conventional tubing, and even a heat shrinkable form (Zeus PEEKshrink®).

Figure 2: Close-up view of PEEK insulated wire examples.

PEEK's properties also make it highly suited to products such as pharmaceutical and food packaging as well as components used in biomedical applications. PEEK can be produced as a drawn fiber or extruded as a monofilament. Capable of fine extrusions, PEEK can be coated over fiber optics as a strengthening layer or over wires as a protective and insulating layer (**Fig. 2**). With PEEK's ability to be made into such a wide array of products, it is not surprising that it has made its way into industries including chemical, medical, oil and gas exploration, automotive, and aerospace.

ELECTRICAL RELEVANCE

PEEK's many exceptional attributes as a thermoplastic mean that new applications for it are always on the horizon. By the late 1970's, polymer engineers began exploring whether PEEK was viable as a coating to electrical wires because of PEEK's dielectric properties [6, 7]. Of particular interest for electric performance is PEEK's behavior as an insulator. PEEK is completely covalently bonded, thus it has no mobile electrons resulting in excellent insulating properties. As a *dielectric*, however, PEEK is easily polarizable allowing it to store electrical energy. The limit of a dielectric to store this energy is its *dielectric strength*. If placed in a voltage that exceeds a material's dielectric strength, the material will fail or break down as an insulator. This failure can manifest as either a thermal or an electrical failure at which the dielectric no longer is viable. (Thus, dielectric strength is also referred to as *breakdown voltage*). In practical terms, the higher the dielectric strength of a material, the better its insulating properties. Dielectric strength is thickness-dependent and typically given in volts per unit thickness, V/mil or kV/mil. For PEEK, depending on its purity and other physical factors, its dielectric strength may range from 0.5 – 20 kV/mil (ASTM D149) enabling PEEK to be used for a wide variety of insulating needs.

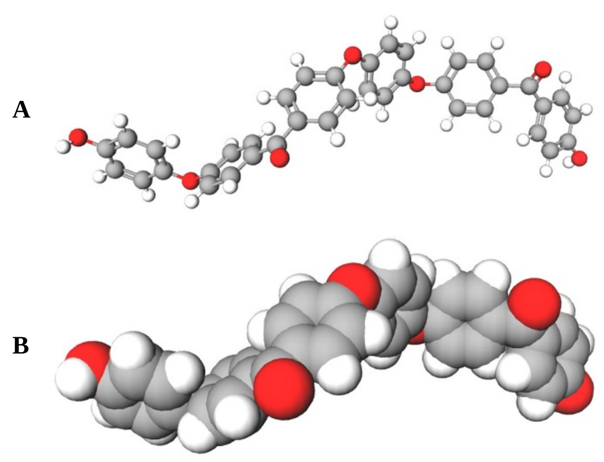

Figure 3: PEEK 2n polymer showing bent and twisted conformation. A) Ball-and-stick model; B) van der Waals spheres model. White = hydrogen; gray = carbon; red = oxygen. (*Shown with terminal hydroxyls*).

PEEK's morphology also plays a role in its insulating abilities. Although PEEK polymeric chains can be viewed as linear overall, their conformation in space is of a bent molecule involving multiple twists (**Fig. 3**). Thus, PEEK morphology is variable from nearly completely amorphous to more crystalline depending on the packing nature of the polymer chains. For thermoplastics in general, more crystalline forms exhibit better insulating characteristics, and this is true of PEEK as well. Furthermore, steps in polymer processing allow morphology to be controlled within certain limits. This attribute has particular relevance for PEEK coated magnet wire for use in electric motors. PEEK's insulating properties thus can be guided during the coating process to conform to physical requirements to produce optimal dielectric strength based on the intended application. Since dielectric strength is partly a function of material thickness as well as morphological properties, it logically follows that the choice of material is weighed carefully under circumstances where high voltages may be likely or when the required thickness of the dielectric – such as a coating over wire – is very small.

Apart from dielectric strength, a material's insulating properties can be described by its *dielectric constant*. This parameter (also known as *permittivity*) describes how a material polarizes at the atomic level compared to the polarizability of a vacuum and therefore the degree to which it can store electrical energy. While dielectrics are insulators because of their polarizability, the more easily they are polarized, the more electrical energy they are able to store making them better insulators. Dielectric constant reflects how much an electric field is dampened or reduced in the presence of the dielectric compared to a vacuum. As an example, the dielectric constant for a vacuum is given as 1, for air 1.00059, and for PEEK ~3.0. The lower the dielectric constant, the better the insulating properties of the material because of its ability to be polarized yet store electrical energy in the presence of an electric field and not conduct electricity. The advantage of an insulating wire coating with such properties thus becomes clear: As an example, PEEK coating on a magnet wire, serving as a dielectric, or *insulator*, reduces the effective electric field between the wire and its external or surrounding environment such as a metal motor frame or ground. Well-insulated wire, therefore, minimizes electrical loss during operation and increases the efficiency of the motor.

The insulating capacity of a material is not confined to planar dimensions. Volume resistivity accounts for the material's resistance (inverse conductance) in three dimensional space, typically given for a volume of unity. Volume resistivity is commonly given as ohms · cm ($\Omega \cdot$ cm). This characteristic, in practical terms, measures how strongly a material opposes the flow of electric current through a cubic volume of the material. The lower the resistivity, the greater the conductivity of the material and vice versa. A commonly held perspective on volume resistivity is that materials with $< 10^5\ \Omega \cdot$ cm resistivity are considered conductive while those with resistivities $> 10^9$ are considered insulators [8]. The volume resistivity for PEEK normally lies in the range of $1.6\text{-}7 \times 10^{16}\ \Omega \cdot$ cm (ASTM D257) identifying PEEK as a good insulator [8].

PEEK INSULATED WIRE FOR ELECTRIC MOTORS

While PEEK's mechanical characteristics impart significant strength and protection to wire as a coating, PEEK's ultimate benefit as an extruded coating for magnet wire and motor applications is its electrical performance attributes. PEEK resists electrical leakage and can be applied in uniform thickness for predictable performance. PEEK's insulating benefits can be achieved with very thin extruded coatings while still retaining significant crystallinity. Yet, the thin extruded layer of PEEK over the wire means that the wire is still highly amenable to manipulation such as bending and wrapping for coil windings. PEEK's chemical resistance is especially preferred since it will likely be exposed to electrical varnishes, solvents, and coolants when used over magnet wire. PEEK-coated wire's tough exterior also protects it from damage and abrasion during normal motor build and wire installation. While no one type of polymer provides all of the optimal traits for improved motor performance, PEEK's across-the-board attributes makes it highly desirable for magnet wire and motor insulation.

COMPARISON OF OEM MOTOR AND MOTOR REBUILT WITH ZEUS PEEK INSULATED WIRE AND OTHER PEEK PRODUCTS

In light of the many potential benefits that PEEK insulation could bring to electric motor performance, we compared performance attributes for an OEM motor and the same motor rebuilt with PEEK insulation products. The motor used for this evaluation was a readily obtainable small 0.75 horsepower, 4-pole, 460 volt, AC induction motor (**Fig. 4**). The OEM-installed wire and insulation system was Class F (Class 155C) and consisted of 24 AWG standard enameled magnet wire 35, Nomex®, Nomex® laminate, Dacron®-Mylar®-Dacron® (DMD) insulation, and Class F lead wire. The rebuilt motor consisted of Zeus crystalline PEEK insulated magnet wire 24 AWG, heavy build (1.1 mils); and PEEK Lay-Flat® tubing for slot liners and phase insulation (**Fig. 5**). This rebuilt motor was Class H (Class 180C), and both motors used a trickle varnish resin insulation. Abbreviated test results are outlined below.

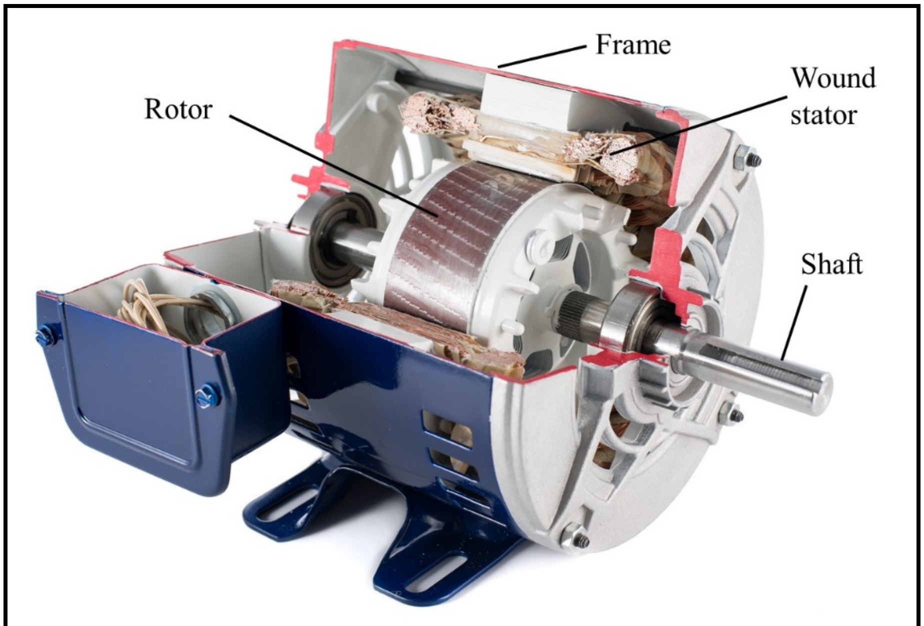

Figure 4: Cut-away of representative test motor showing basic motor components described in this work.

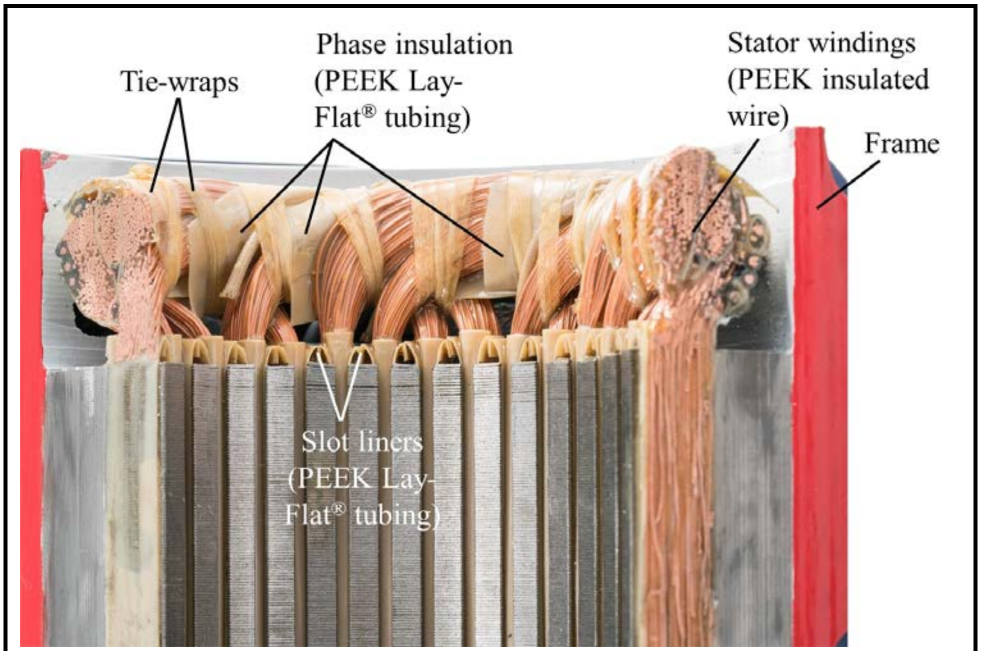

Figure 5: Cross-sectional view of rebuilt motor with rotor and shaft assembly removed. The rebuilt motor contained PEEK insulated magnet wire (stator windings), PEEK Lay-Flat® tubing used as phase insulation, and PEEK Lay-Flat® tubing for slot liners.

Electrical testing was done using an Amprobe® AMB55 high voltage insulation resistance tester, an ALL-TEST PRO 5™, an ALL-TEST PRO OL™, and an Electrom iTIG 12D. We found that for basic operating criteria, the motor rebuilt with Zeus products showed nearly identical outputs to the OEM motor: capacitance to ground, low ohm resistance, impedance, inductance, current/frequency (I/F) response, insulation to ground, and capacitive phase angle were similar for both motors

(**Table 2**). Polarization index was next tested (in accordance with IEEE Std 43-2013 Annex D; AMPROBE® AMB55). The OEM motor polarized to 10 GigaOhm over the course of the ten minute test (data not shown; *for complete test data, see our Test Report: Impact on Low Voltage Motor Performance* here). The motor rebuilt with Zeus products polarized to 1 TeraOhm in 12 seconds before varnish was applied; polarization was reduced to 5 seconds after trickle varnish was applied.

Table 2: Comparison of basic motor operation criteria of OEM motor and motor rebuilt with Zeus PEEK insulation products.

Test	Original Motor	Zeus Materials
Resistance	37.7 Ohms	38.0 Ohms
Inductance	159 mH	159 mH
Impedance	106 Ohms	107 Ohms
Phase Angle	68.8 degrees	68.6 degrees
I/F	-47%	-46.9%
Insulation Resistance	>1 GigOhm	>1 GigOhm
Capacitance	<2 µF	<2 µF

Table 2: Test results for low ohm resistance, inductance, impedance, capacitive phase angle, current/frequency (I/F) response, insulation to ground, and capacitance to ground for original motor and motor rebuilt with Zeus-manufactured products. No significant differences were observed between the OEM and Zeus-rebuilt motors. This testing was performed using an ALL-TEST PRO 5™.

We next tested the condition of the motor insulation system using an Electrom iTIG D12 for low and high voltage assessment. Partial discharge (PD) was measured for the OEM and rebuilt motors to detect voids within the insulation which can lead to failure in variable frequency drive (VFD) applications. The windings of the OEM motor and motor rebuilt with Zeus PEEK products appeared similar based on previous tests. PD tests revealed, however, that the OEM motor was susceptible to failure with a PD of 668,070 pC, while the rebuilt motor showed a PD of only 703 pC (data not shown; *see Test Report*). For other performance factors, the rebuilt motor showed improvements over the OEM motor for Q factor, D factor, and capacitance (**Table 3**). These improvements were consistent for each of three different lead configurations that were tested. The rebuilt motor also performed at slightly higher efficiency than the OEM motor, 1746 rpm vs 1715 rpm, respectively, despite the slightly higher voltage harmonics of the Zeus PEEK motor (data not shown) [Oak Ridge Motor Efficiency and Load software (ORMEL ′96)].

Table 3: Comparison of performance factors of OEM motor and motor rebuilt with Zeus PEEK insulation products.

Low Voltage C/L/Z Test Data

	C (nF)	D Factor	L (mH)	Impedance	Ø Angle	Q Factor
Lead 1-2	0.137	0.012	153.930	969.40	86.1	14.59
Lead 2-3			153.640	967.60	86.1	14.52
Lead 1-3			154.120	970.60	86.1	14.51
Balance			0.3%	0.3%	0.0%	0.6%

Low Voltage C/L/Z Test Data

	C (nF)	D Factor	L (mH)	Impedance	Ø Angle	Q Factor
Lead 1-2	0.147	0.011	153.690	968.30	85.8	13.53
Lead 2-3			153.890	969.50	85.8	13.54
Lead 1-3			153.460	966.80	85.8	13.64
Balance			0.3%	0.3%	0.0%	0.8%

Table 3: Results of low voltage testing for capacitance (C), dissipation (D) factor, inductance (L), impedance, phase angle (Ø), and quality (Q) factor: original motor insulation system (*top*) and Zeus insulation system (*bottom*). (Testing was done using an Electrom iTIG D12).

Throughout the testing, the motor rebuilt with Zeus PEEK insulated magnet wire (and other PEEK products) exhibited equal to or better performance attributes than the OEM motor in multiple areas. The motor rebuilt with Zeus PEEK products showed lower leakage and shorter absorption times; this motor also exhibited greater efficiency with less insulation system losses. These results suggest less aptitude for failure in inverter applications following motor rewind with Zeus PEEK insulated magnet wire (and other PEEK products). Collectively, our testing highlighted the superior insulating properties of PEEK and how these properties can be applied in a practical yet highly beneficial way.

SUMMARY

Polyether ether ketone, commonly referred to as PEEK, is a highly versatile thermoplastic polymer. Among PEEK's many beneficial properties is its ability to be melt processed into a multitude of different forms. PEEK's properties give parts made with this polymer very high hardness and wear resistance. These parts also exhibit exceptional chemical resistance. PEEK's temperature tolerance sets it apart from many PAEK (polyaryl ether ketone) family members with its ability to withstand working temperatures to 260 °C (500 °F). Thus, PEEK has become a preferred material for an extensive and diverse array of applications.

As knowledge and interest in polymer plastics grew, these materials became particularly favored for use as insulators. Their processability allows a degree of control over many of their properties such as thickness, shape, and crystallinity pertinent to use in electrical settings. As a representative dielectric from this group, PEEK is polarizable and exhibits many properties especially favorable for use in electric motors. PEEK's mechanical attributes enable it to be extruded over wire for motor coil windings, and PEEK's heat resistance easily withstands the high temperatures that could be reached under continuous motor operation. Indeed, polymer plastics including PEEK have become commonplace in many electrical applications.

To explore whether PEEK could be used to affect motor performance in a beneficial way, we compared a small commonly obtainable 0.75 horsepower, 4-pole, 460 volt, AC induction motor with original equipment insulating materials and magnet wire to the same motor rebuilt with Zeus PEEK insulation products including PEEK insulated magnet wire and PEEK Lay-Flat® tubing for phase insulation and as slot liners. We found that for basic motor operation, the OEM and rebuilt motors exhibited nearly identical outputs for capacitance to ground, insulation to ground, inductance, low ohm resistance, impedance, current/frequency (I/F) response, and capacitive phase angle. For polarization index, the motor rebuilt with Zeus PEEK products polarized to 1 TeraOhm compared to the 10 GigaOhm of the OEM motor. For other test outcomes, the motor rebuilt with Zeus products showed improvements over the OEM motor in D factor, Q factor, and capacitance. The rebuilt motor also showed slightly higher rpm than the OEM motor under the same load suggesting a gain of efficiency for the rebuilt motor. In totality, the motor rebuilt with Zeus PEEK insulated wire (and other PEEK products) showed performance equal or better than the OEM motor highlighting the superior insulating characteristics of PEEK insulated wire and other PEEK products and the potential to improve motor performance and efficiency.

For more information, please see complete Test Report, Impact on Low Voltage Motor Performance. Supplemental information can be found in our Case Study, Motor Rewind with Zeus PEEK Insulation Products, describing the manufacturability of PEEK motor components.

ABOUT ZEUS

Zeus is the world's leading polymer extrusions and material science innovator. For over 50 years, we have been serving the medical, aerospace, energy exploration, automotive, and fiber optics industries. Headquartered in Orangeburg, South Carolina, Zeus employs approximately 1,250 people worldwide and operates multiple facilities in North America and internationally. You can find us at www.zeusinc.com.

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