Engineering polymers with high mechanical and thermal resistance for electric motors

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Abstract

The aim of the research was to select and evaluate polymers that could be used as rotor insulation in electric motors based on Halbach array system. Which have specific material properties, such as high mechanical strength, high thermal resistance and, especially, high thermal conductivity, also at room and at elevated temperatures. Three high performance polymers were selected for the research: polyetheretherketone (PEEK), polyamideimide (PAI) and poly(p-phenylene sulphide) (PPS). Polymers were evaluated for mechanical strength, thermal conductivity, thermal diffusivity, specific heat capacity, linear thermal expansion and also differential scanning calorimetry (DSC) and thermal gravimetry (TG) analyses were carried out. Analyses proved that all materials have appropriate properties for advanced electric motor insulator.

Key words: high-performance polymers, high thermal conductivity, electric motors materials, PEEK PAI PPS

Introduction

Nowadays the electric motors are widely used in many fields of industry and everyday applications. Also, in the fields where, low mass with high effectivity is crucial, which implicates engineering polymers application in construction of electric motors [1]. Engineering polymers, and especially high-performance polymers, are a subset of polymeric materials that are used in applications generally requiring higher performance in the areas such as thermal resistance, chemical resistance or mechanical strength [2].

There are several requirements for polymers, to be suitable as electric wire insulator (especially magnet wire insulator). First, there should have high thermal resistance. There are several classes of electrical insulators. The best (class H), according to International Standards IEC 60085 should have short service temperature at 180 °C, or even as high as 220 °C according to the newest standards [3, 4]. They should have good thermal dimensional stability, so the coefficient of linear thermal expansion should be low, ideally as low as coefficient of copper ($17 \cdot 10^{-6}$ K^{-1}) [5]. These materials should also show good resistance to external forces such as bending, stretching and friction, as well as good chemical resistance and good electrical characteristics such as dielectric strength and insulation resistance [6].

High thermal conductivity of a material is important to effectively dissipate heat in a system, especially at elevated temperatures, which are working conditions for electric motors [7]. Most studies on thermal conductivity of polymers has been focused on the research performed at room temperature [8] and only a few at the elevated one, even if many materials are working in high temperatures, higher than 100 °C. High thermal conductivity and low thermal expansion lead to good resistance to heat shock, which is also important parameter of electrical insulator [9].

The aim of our research was to select and evaluate polymers that could be used as rotor insulation in electric motors based on Halbach array system. The polymer should have specific material properties, such as high mechanical and thermal resistance, including high maximum continuous service temperature, and especially, high thermal conductivity, also at room and at the elevated temperatures. These parameters are usually evaluated in real service conditions of electric motors [8].

Three high performance polymers were selected for further research: polyetheretherketone (PEEK), polyamideimide (PAI) and poly(p-phenylene sulphide) (PPS). The literature data indicate these polymers possess properties seemly for the application in electric motors (Table 1). However, these polymers are already of quite broad use, many properties important for specific applications are still missing in the literature.

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Table 1. Literature properties of the selected polymers [2, 5, 10–17]

	PPS	PAI	PEEK
Melting temperature [°C]	280-295	357	334-374
Glass transition temperature [°C]	74-92	206-326	143-158
Coefficient of thermal conductivity [W/(m•K)]	0.24-0.30	0.26-0.54	0.25
Tensile strength [MPa]	70-102	110-160	75-100
Tensile modulus [GPa]	3.4-4.2	4.5-6.8	3.5-4.7
Elongation at break [%]	3-8	5-35	5-50
Flexural strength [MPa]	125-145	196-241	146-170
Flexural modulus [GPa]	3.7-4.2	3.6-5.0	3.7-4.3
Maximum continuous service temperature (20000 h) [°C]	220	250-260	250-260
Maximum short service temperature [°C]	260	270-400	310-400
Specific heat capacity [J/kg·K]	770-795	1013	2160
Density [kg/m^3]	1340-1360	1380-1450	1260-1400
Thermal expansion coefficient at RT [•10^{-6} K^{-1}]	49-55	17-35	43-160
Decomposition temperature [°C]	450-532	450	575

Materials and methods

Polyetheretherketone (Kestron 1000 PEEK) and polyamideimide (Duratron T4203 PAI) were purchased from Quadrant Engineering Plastics Products (Germany), while poly(p-phenylene sulphide) (Fortron® PPS) was purchased from Resinex (Poland). Samples were prepared by uniaxial hot pressing using parameters of processing presented in Table 2, and then cut to appropriate forms. Prior to hot pressing polymers were dried for 24h at 120°C.

Table 2. Processing parameters of uniaxial hot pressing

Processing parameters	PPS	PAI	PEEK
Temperature [°C]	335	350	380
Pressure [MPa]	80	80	80
Time of pressing [min]	30	30	30

Mechanical properties were evaluated by tensile and three-point bending tests using a Zwick 1435 universal testing machine. The cross-head velocity was 2mm/min for both tests. Samples were cut into 60 mm length rectangular bars (~ 3 mm x 4 mm in cross section).

The thermal conductivity, thermal diffusivity and specific heat capacity were measured at various temperatures (25 °C, 70 °C, 120 °C, 180 °C and 250 °C) by laser flash method using a NETZSCH LFA 427. The measurements were carried out under a constant argon flux (150 ml/min).

The measurements of coefficient of linear thermal expansion have been carried out using a NETZSCH IL 402 C dilatometer in the range of 20°C to 235°C at a heating rate of 5 °C/min under a constant nitrogen flux (150 ml/min).

The differential scanning calorimetry (DSC) and thermal gravimetry (TG) were obtained using NETZSCH STA 449 F3 Jupiter in the temperature range of 20°C to 1000°C at a heating rate of 10 °C/min under a constant nitrogen flux (50 ml/min). The samples (~7 mg) were encapsulated into a sample holders of aluminum oxide.

Results and discussion

The results obtained for mechanical properties measurements of the polymers are shown in Table 3. The highest tensile strengths, about 75 MPa, have PPS and PEEK, which is in agreement with the literature data. The tensile strength of PAI was about 50 MPa which is lower than in the literature [13]. The tensile modulus was similar for all three polymers and was about 7-8 GPa, which is slightly less than in the literature [13]. Elongation at break were from 2.06 % to 4.32 %, also slightly less than in the literature, however the values were quite comparable. The flexural strength was from 92 MPa for PPS to 192 MPa for PEEK, which was slightly less for PPS and PAI than in the literature, while PEEK's flexural strength was higher than in the references [10] and [13]. The flexural modulus was about 3 GPa for all polymers, which is consistent with the literature data [5, 13].

The results of DSC and TG are shown in the Figures 1-3. Decomposition of polymers starts at 440 °C for PAI, 450 °C for PPS, and 550 °C for PEEK. Glass transition temperatures were established for 150 °C for PEEK, and 340 °C for PAI (glass transition effects wasn't observed for PPS), whereas melting was observed at 285 °C for PPS and 340 °C for PEEK, while no melting effects was observed for PAI, which is agreement with the literature data [5, 13].

The results of the linear thermal expansion measurements were shown in Figure 4. The lowest coefficient of linear thermal expansion at RT i.e., $29\cdot10^{-6}$ K^{-1} shows PAI, slightly higher values, namely $40\cdot10^{-6}$ K^{-1} and $51\cdot10^{-6}$ K^{-1} were obtained for PPS and PEEK, respectively, which are, except slightly lower value for PPS, in agreement with the literature data (Table 1) [5, 13]. At the temperature of 70°C the coefficient for PAI increased $50\cdot10^{-6}$ K^{-1}, and remained stable to 220 °C, and then decreased above 200 °C to $45\cdot10^{-6}$ K^{-1}. The coefficient of linear thermal expansion for PPS is stable to 80 °C (which is around of glass transition temperature), and then increases to $50\cdot10^{-6}$ K^{-1} at 100 °C, then remains stable to 200 °C, and then increases to value $89\cdot10^{-6}$ K^{-1} at 230 °C. For PEEK, the coefficient of linear thermal expansion slightly increases to $62\cdot10^{-6}$ K^{-1} at 135 °C, then at 160 °C, that is close to the glass transition temperature, it significantly rises to $145\cdot10^{-6}$ K^{-1}, and then at 230 °C its value reaches $190\cdot10^{-6}$ K^{-1}. The coefficients of linear thermal expansion of all investigated polymers are extremely low and comparable to these of cross-linked polymers, which for epoxy resin are reported as $62\cdot10^{-6}$ K^{-1} at 20 °C, $75\cdot10^{-6}$ K^{-1} at 100 °C, and $130\cdot10^{-6}$ K^{-1} at 150 °C [5]. Cross-linked (cured) polymers are the less thermally expandable polymers by nature. However, they cannot be thermally processed, and for that reason linear thermoplastic PPS, PAI and PEEK can be considered as the more appropriate choice. As the investigated polymers are expected to work together with copper wires, to omit the failures arising from thermal stress, the linear expansion of both, metal and polymer materials should be comparable.

The thermal diffusivity of the polymers is shown in Figure 5. The values for PPS and PEEK were similar, variating from $1.17\cdot10^{-6}$ m^2/s at room temperature (RT) to $0.1\cdot10^{-6}$ m^2/s at 250 °C. Thermal diffusivity of PAI ranged from $0.21\cdot10^{-6}$ m^2/s at room temperature to $0.13\cdot10^{-6}$ m^2/s at 250 °C. The thermal diffusivity of the examined polymers was significantly higher than this of other polymeric construction materials such as polyamides ($0.14\cdot10^{-6}$ m^2/s at RT, $0.11\cdot10^{-6}$ m^2/s at 100 °C), poly(vinyl chloride) ($0.13\cdot10^{-6}$ m^2/s at RT, $0.09\cdot10^{-6}$ m^2/s at 100 °C) or polypropylene ($0.12\cdot10^{-6}$ m^2/s at RT, $0.10\cdot10^{-6}$ m^2/s at 100 °C) [18].

The specific heat capacity was the highest for PPS (as shown in Figure 6), 1100 J/kg·K at room temperature and 1600 J/kg·K at 250°C. PEEK and PAI show slightly lower values, about 900 J/kg·K, 1000 J/kg·K, 1200 J/kg·K and 600 J/kg·K, at room temperature, 70 °C, 180 °C and 250 °C, respectively. The values obtained for PEEK were lower than presented in the literature [14] (probably due to different crystallinity of testing and literature PEEKs), also non-typical was that the specific heat capacities of PEEK and PAI decreased at temperatures exciding 170 °C. Usually polymers' behavior is the contradictory [15]. Explanation of this phenomena is possibly changing of crystallinity of the polymers (if it increases, heat capacity decreases) or crosslinking process during period of measurements at 250 °C.

The coefficients of thermal conductivity were shown in Figure 7. At room temperature, thermal conductivities were the highest for PPS and PAI ((0.26 ± 0.01) W/m·K and (0.26 ± 0.03) W/m·K, respectively), while for PEEK it was determined as (0.20 ± 0.01) W/m·K. The coefficient of thermal conductivity of PAI increased to (0.30 ± 0.01) W/m·K at 120 °C and then decreased to (0.28 ± 0.01) W/m·K at 170 °C and (0.12 ± 0.02) W/m·K at 250 °C. The coefficient obtained for PPS also increased to (0.28 ± 0.01) W/m·K at 70 °C and then decreased to (0.27 ± 0.01) W/m·K at 120 °C, (0.24 ± 0.01) W/m·K at 170 °C and (0.22 ± 0.01) W/m·K at 250 °C. Instead, the coefficient of PEEK decreased in the whole temperature range, from (0.20 ± 0.01) W/m·K at RT at 70 °C through (0.17 ± 0.01) W/m·K at 120 °C and 170 °C to (0.07 ± 0.01) W/m·K at 250 °C. At the room temperature, the coefficients of thermal conductivity of PPS and PAI were consistent with the literature data, but PEEK's was lower [5, 8, 13]. Moreover, at elevated temperatures (especially up to 170 °C) conductivities become stable, or even a little higher. It is important because the coefficient of thermal conductivity generally decreases at higher temperatures (especially above glass transition temperature for amorphous polymers) [8, 19].

Table 3. Mechanical properties of PPS, PAI and PEEK

	PPS	PAI	PEEK
Tensile strength [MPa]	74.6 ± 7.3	50.8 ± 12.9	75.2 ± 16.9
Tensile modulus [GPa]	8.62 ± 0.66	7.59 ± 1.90	7.19 ± 0.24
Elongation at break [%]	2.99 ± 0.57	2.06 ± 0.33	4.32 ± 1.25
Flexural strength [MPa]	91.6 ± 9.9	155.5 ± 20.0	192.4 ± 33.4
Flexural modulus [GPa]	3.28 ± 0.14	2.92 ± 0.67	3.21 ± 0.44

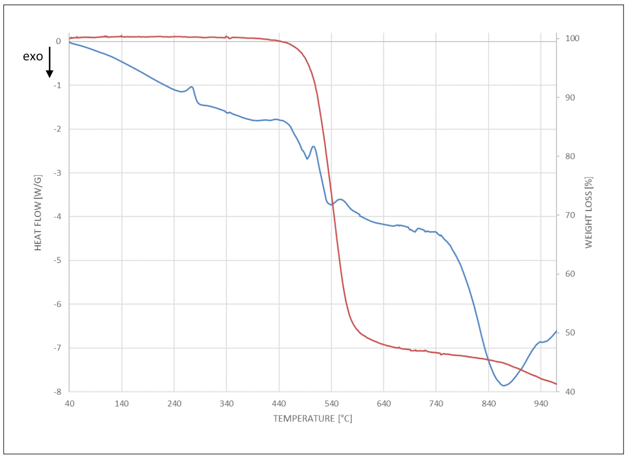

Figure 1. DSC (blue line) and TG for PPS (red line)

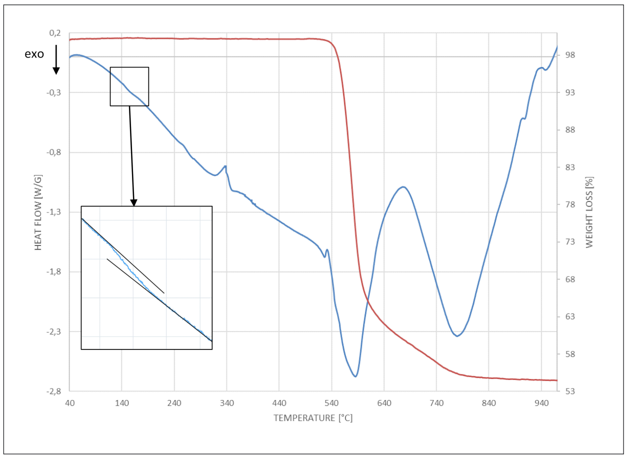

Figure 2. DSC (blue line) and TG (red line) for PEEK

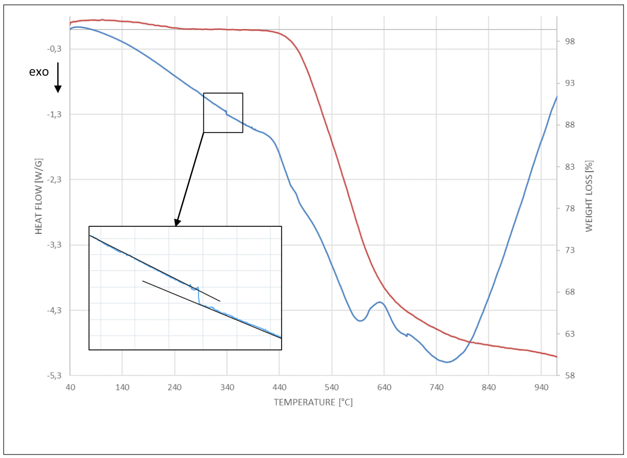

Figure 3. DSC (blue line) and TG (red line) for PAI

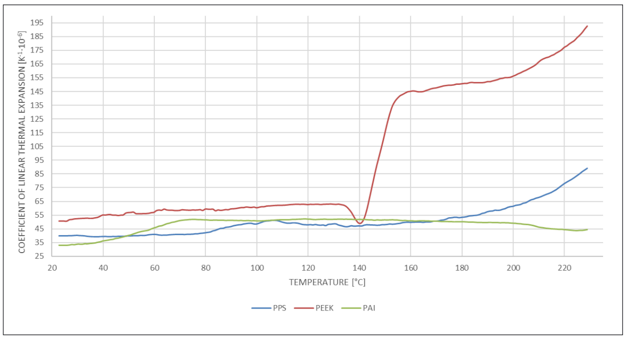

Figure 4. Coefficient of linear thermal expansion of PPS, PAI and PEEK

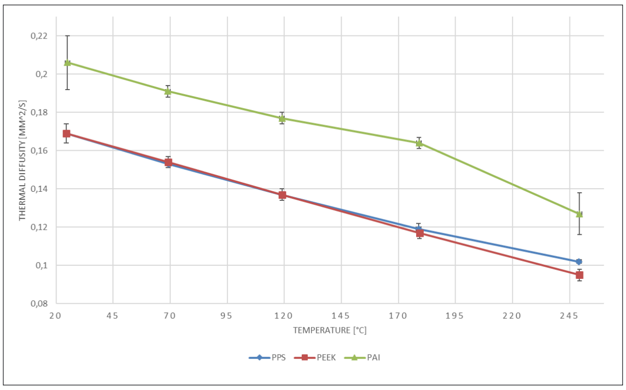

Figure 5. Thermal diffusivity of PPS, PAI and PEEK

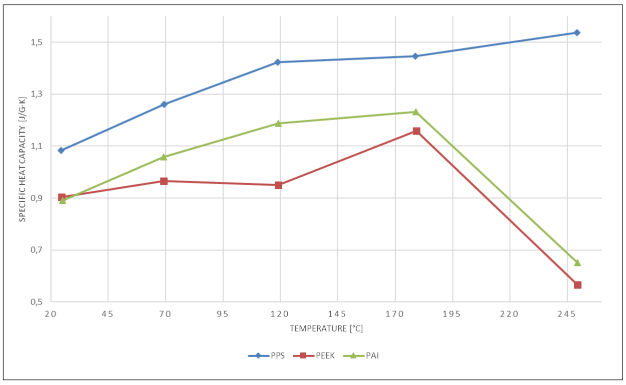

Figure 6. Specific heat capacity of PPS, PAI and PEEK

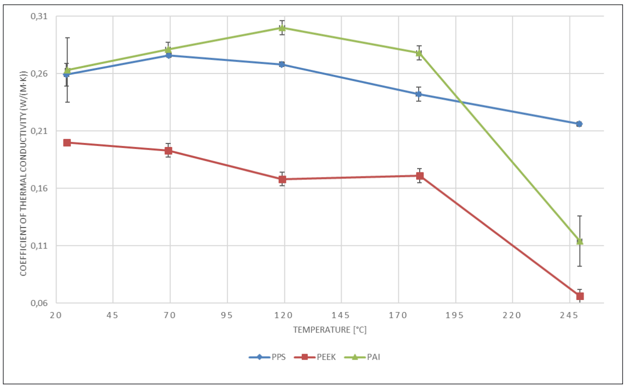

Figure 7. Thermal conductivity of PPS, PAI and PEEK

Conclusions

The studies showed that the investigated engineering polymers – polyetheretherketone (PEEK), polyamideimide (PAI) and poly(p-phenylene sulphide) (PPS) are good candidates for electric motors insulation and meet expectations for application as electricity insulators in electric motors. They have appropriate mechanical strength and thermal resistance and also high thermal conductivity and low linear thermal expansion. Moreover, thermal conductivity at elevated temperatures are also relatively high. The most promising polymer for this application is PAI due to extremely high thermal dimensional stability and high thermal conductivity (especially to 200 °C) compared to another investigated materials.

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