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Nanofiller-modified varnishes for electrical insulation

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Investigation into improvements in impregnating varnishes used for electrical insulation. The comparative results of the thermoanalytical testing and temperature dependence of the bonding strength of varnishes with various cross-linking reactive agents in the standard version and in the modified by introducing nanofillers version are presented. On the basis of the testing it was found that the thermal and mechanical properties of the varnishes modified by nanofillers have been greatly improved. New varnishes modified by nanofillers may be useful for a very high speed or inverter-fed electrical motors applications.

Key words: *impregnating varnish; nanofiller; bond strength; thermoanalytical methods; thermal endurance*

1. Introduction

Properties of available impregnating varnishes do not satisfy requirements of some applications, e.g. in very high-speed electrical motors (bond strength is not sufficient) or in inverter-fed motors (vulnerable to partial discharges). The varnishes need to be modified to improve their properties.

Insulating varnishes can be divided into two groups: solvent varnishes and solventless varnishes (with reactive diluents). Solventless varnishes can be improved by incorporating various reactive diluents that can increase bond strength and thermal endurance. Reactive monomers, other than styrene, are usually more expensive. In this project, we chose still another way of improving bonding properties of varnishes by incorporating a new class of fillers, i.e. nanofillers.

Nanofillers influence material properties at molecular level, and have potential to be far more homogeneously distributed than regular fillers and thus are effective at low concentrations (1–10 wt. %), keeping the cost down. Although interaction between

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nano-scale structures and polymer matrices is still unknown, nano-composites offer significant improvement of performance over base polymers. They can be designed for desired application requiring enhanced tensile strength, conductivity, thermal resistance, flammability, etc. [1–4].

The goal of this project was to fabricate nanofilled varnishes and investigate their properties for modern electrical motor applications.

3. Experimental

3.1 Samples

Six types of solventless varnishes with various reactive monomers (styrene, biallyl phtalate, vinyltoluene) and one type of solvent varnish with and without nanofiller were used (Table 1). The nanofiller was based on surface-modified layered silicates consisting of a sheet-like structure where the dimensions in two directions far exceeded the particles thickness. The thickness of the layers (platelets) was of the order of 1 nm and the aspect ratio was above 100. The type of nanofiller and its concentration were selected based on the results of processability and thermoanalytical tests.

3 wt. % of nanofiller was applied to solventless varnishes and 2 wt. % to solvent varnish. The nanofillers were dispersed in dissolved varnishes at ambient temperature.

Table 1. Tested varnishes based on unsaturated polyestreimide resin

No.	Reactive diluent	Number of components, impregnating method	Code
Solventless varnishes			
1	diallyl phtalate (P)	one-component (1) dipping varnish (D)	P1D
2	styrene (S)	two-components (2) trickle varnish (T)	S2T
3	styrene (S)	one-component (1) trickle varnish (T)	S1T
4	vinyltoluene (V)	one-component (1) dipping varnish (D)	V1D
5	styrene (S)	two-component (2) trickle varnish (T)	S2T′*
6	styrene (S)	two-component (2) dipping varnish (D)	S2D
Solvent varnish			
7	blend of solvents	dipping varnish (D)	D

*S2T′ – the same type of varnish as S2T but from different manufacturer.

3.2 Processing parameters

Varnishes are applied in motors by conventional impregnating methods, such as dipping or trickling and their processing parameters must suit the method used. The results of measurements of impregnation parameters (viscosity, gelation time and gel temperature) for standard and modified by nanofiller varnishes are compared in Table 2.

Table 2. Viscosity, gelation time and gel temperature for standard varnishes and modified by nanofiller

No.	Varnish	Catalogue data		Testing data			
		Standard varnish		Standard varnish		Modified varnish	
		Viscosity /s	Gelation time /min /gel temperature / °C	Viscosity /s	Gelation time /min /gel temperature / °C	Viscosity /s	Gelation time /min /gel temperature / °C
1	P1D	340–370	20–60/110	340	40/110	352	45/110
2	S2T	45–105	3/120	38	3/120	46	3.5/120
3	S1T	45–105	1.5–2/120	58	1.5/120	62	2/120
4	V1D	150–170	2–3/130	155	3/130	162	3/130
5	S2T	22–26	2–3/120	27	3/120	28	3/120
6	S2D	100–120	6/120	114	6/120	131	7/120
7	D	60–80	4–6 h/120	85	5h/120	92	5.5h/120

It can be noticed that the varnish with diallyl phtalate as a reactive monomer (PID) shows the highest viscosity and gelation time. The data presented in Table 2 indicate that the varnish viscosity and range of the gelling parameters are not significantly changed by the presence of a nanofiller. The fact that the processing parameters do not deteriorate due to application of nanofiller is substantial for the impregnation processes of motor windings.

3.3. Thermoanalytical testing

Standard and the modified varnishes in a liquid and cured conditions have been tested using thermoanalytical methods. The test parameters applied were the following: temperature range: 25–800 °C, rate of furnace temperature rise: 10 °C/min, sample mass: 100 mg, test environment: air, reference substance: Al_2O_3. One measurement was performed for each varnish.

On the basis of the simultaneous recording of TG, DTG, DTA and T curves, the range of gel temperature, loss of mass during gelling and solid content for liquid varnishes and the initial temperature of decomposition (5% loss of mass) for cured varnishes have been determined. For cured samples the relative temperature index RTI_{TG} by the Di Cerbo method [5] has also been assessed.

The varnishes show maximum temperature of exothermic peak between 130–180 °C. The loss of mass during gelling is 10–17% for all solventless varnishes with and without nanofillers, except for the varnish with diallyl phtalate PID (6%). The lowest initial temperature of decomposition (270 °C) and relative temperature index (139) were also obtained for the PID, while for all of the other solventless varnishes the initial temperature of decomposition was in the range of 300–320 °C and relative temperature indexes in the range of 146–171.

Table 3. The result of thermoanalytical testing of the standard and modified varnishes

No.	Varnish	Liquid varnish					Cured varnish	
		Range of gel temperature /°C			Loss of mass during gelling** /%	Solid content** /%	Initial temperature of decomposition /°C	Relative temperature index $\mathrm{RTI}_{\mathrm{TG}}$ /°C)
		T_i	$T_{\max}$	T_t				
1	P1D	150	180	230	6	96	270	139
1*	P1D*	150	180	230	6	96	275	–
2	S2T	80	140	160	17	83	300	146
2*	S2T*	80	130	160	15	85	310	–
3	S1T	120	150	190	16	84	300	160
3*	S1T*	110	145	200	16	84	320	–
4	V1T	120	150	190	10	90	320	171
4*	V1T*	120	145	200	10	90	320	157
6	S2T	95	135	180	11	89	320	159
6*	S2T *	100	140	190	13	87	330	–
6	S2D	80	130	170	14	76	310	146
6*	S2D*	80	140	200	14	76	320	162
7	D	120	160	220	55	45	270	171
7*	D*	80	155	230	55	45	320	–

*Varnishes with a nanofiller.
** The accuracy of reading from TG curves was ±2%.

Thermoanalytical testing has confirmed that important processing parameters of varnishes have not significantly changed after adding nanofillers. Table 3 shows that the initial temperature of decomposition of modified styrene varnishes has actually increased by about 10–20 °C in comparison with the standard ones. However, for varnishes with diallyl phtalate (P1D) and with vinyltoluene (VID) the initial temperature of decomposition did not change after modification.

3.4. The bond strength testing

The testing of the bond strength has been made at a temperature range from 23 °C to 180 °C according to IEC standard [6]. At each point six measurements were performed and the scatter of the results was ±6%.

Table 4 shows the ratios of the varnish bonding strength with filler and the bonding strength without filler for various temperatures. This ratio, denoted here as a *k*-factor, is higher than one and thus indicates that the bond strength of a varnish increases after adding a nanofiller. At the test temperatures close to the curing temperature of a varnish (130 °C for styrene varnishes), the *k*-factor attains the maximum value.

Table 4. The *k*-factor for various varnishes at different test temperatures

Varnish	Reactive monomer	The factor *k* at various test temperatures/°C				
		23	105	130	155	180
P1D	diallyl phtalate	0.79	–	0.79	0.76	0.94
V1D	vinyltoluene	0.98	–	1.19	1.32	1.00
S1T	styrene	1.01	–	1.20	1.18	1.30
S2T	styrene	1.22	–	1.53	1.25	1.16
S2D	styrene	1.32	1.76	1.63	1.50	–
PK 180	styrene	1.34	–	1.57	1.25	1.30
D	blend of solvents	1.44	–	1.67	1.40	1.38
S2T	styrene	1.50	1.45	1.52	1.38	1.57

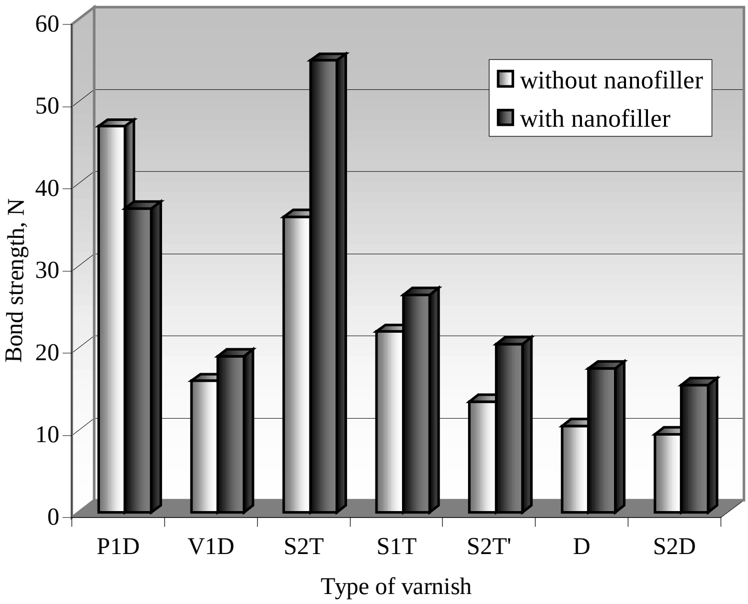

Fig. 1. The bond strength for varnishes with and without nanofiller at 130 °C

In Figure 1, the bond strength of different varnishes with and without nanofillers measured at 130 °C is presented. Figure 2 shows the temperature dependence of the bond strength for the S2T varnish with and without nanofiller.

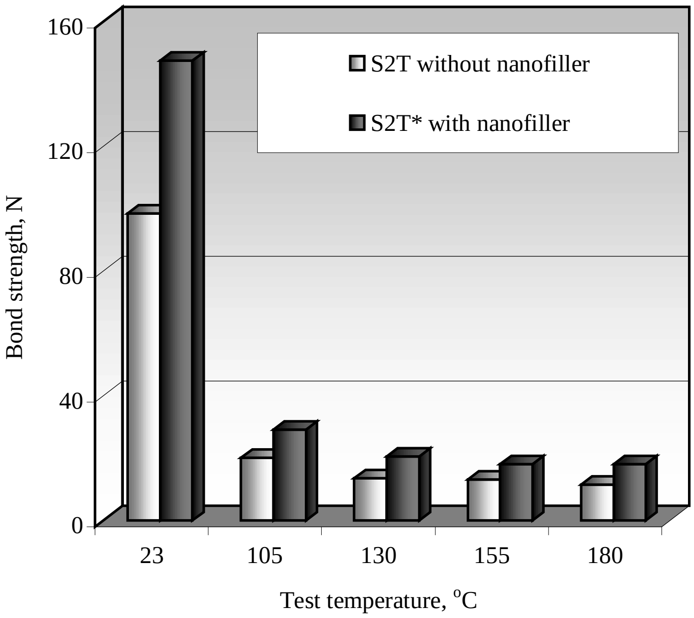

Fig. 2. The temperature dependence of bond strength for varnish S2T with and without nanofiller

The data presented in Table 4 and in Figs. 1, 2 indicate that after incorporation of nanofillers the bond strength of most varnishes significantly increases, up to 67%, except for PID and VID. While for VID varnish (containing vinylotoluene) no improvement was observed, the PID's (varnish with diallyl phtalate) bond strength decreased after modification. Due to high viscosity of these two non-styrene varnishes (Table 2), the nanofiller did not have any positive effect on their thermal and mechanical properties (Tables 3 and 4). For highly viscous varnishes the interlayer spacing of the applied processing method was too most likely small for polymer chains to penetrate.

Conclusions

The comparative test for varnishes used in motor insulation and modified by loading low amounts of nanofiller have been presented. It was found that adding 2–3% of nanofiller to varnishes with various cross-linking agents:

- did not change processing parameters,

- increased the bond strength of styrene varnishes by about 30%,
- increased the thermal endurance of styrene varnishes.

For highly viscous (non-styrene) varnishes development of a better method of dispersing nanofiller particles is required. New nanofiller-modified styrene varnishes exhibit improved mechanical and thermal properties and might be useful for applications in high-speed motors. The nanofiller-modified varnishes will be tested for inverter fed electrical motor applications, including the effect of partial discharges.

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