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Self-lubricating Heat-Resistant Enameled Wire for More Efficient Electrical Motors

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ABSTRACT: We have developed a self-lubricating heat-resistant enameled wire, KMK-20E, to meet the demand for highly efficient motors that have a large space factor, which reduces copper loss. It has superior lubricity, mechanical characteristics, and varnish-bonding strength compared with conventional enameled wires. Its use in conventional motors improves the space factor by 10 to 15%, thus increasing motor efficiency.

〔1〕INTRODUCTION

The continuing worldwide need to save energy has focused the attention of many researchers on the development of highly efficient electric motors. One of the most effective methods for saving energy is to use motors that have a large space factor, which reduces copper loss.

As summarized in **Fig. 1**, there are three important requirements for electrical motors: high efficiency, high quality, and low cost. We have been working on improving efficiency. A key to achieving this is to reduce the generation losses, which for enameled wire generally means copper loss. Effective ways to reduce copper loss include improving the space factor (i.e., the percentage of the slot cross-section taken up by the enameled wire cross-sections) and making the coil-end smaller.

The relationship between the space factor and the winding-examination pass rate of motor coils made of conventional self-lubricating heat-resistant enameled wire is shown in **Fig. 2**. The pass rate drops abruptly when the space factor exceeds 65%. The space factor of motors using conventional self-lubricating heat-resistant enameled wire is thus said to be 65% or less. The reason for the abrupt drop in the pass rate is that when enameled wires are wound very closely and tightly, as shown in **Fig. 3**, external forces on the wires more readily create scratches and pinholes.

To enable enameled wires to be wound more tightly, we have developed a self-lubricated heat-resistant enameled wire, KMK-20E, that; it has superior lubricity, mechanical characteristics, and varnish-bonding strength. Its use can result in a space factor of 70% or more.

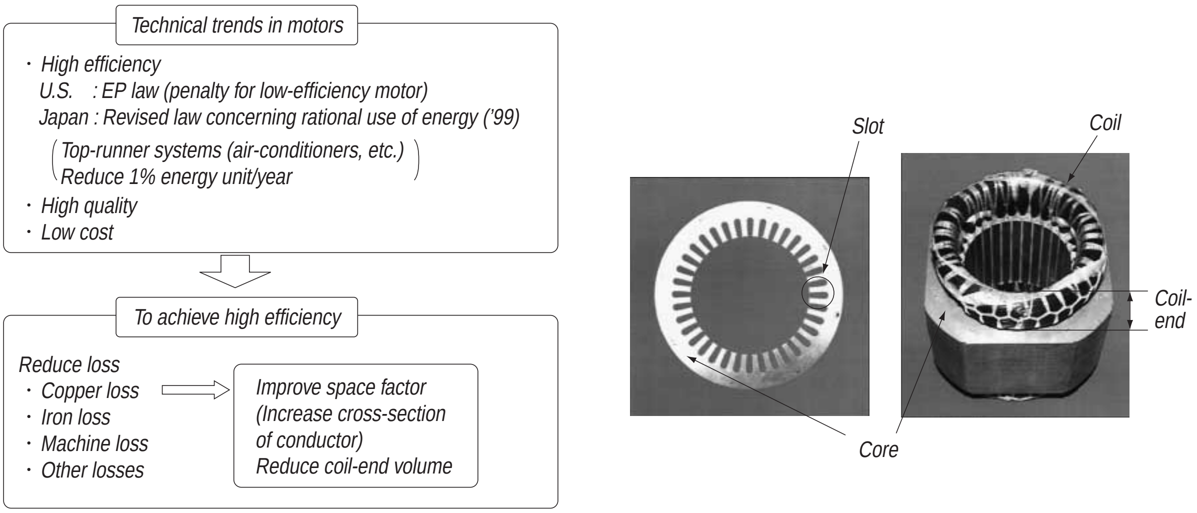

Fig. 1—*Technical trends in motor*
The continuing worldwide need to save energy has focused the attention of many researchers on the development of highly efficient electric motors. One of the most effective methods for saving energy is to use motors that have a large space factor, which reduces copper loss.

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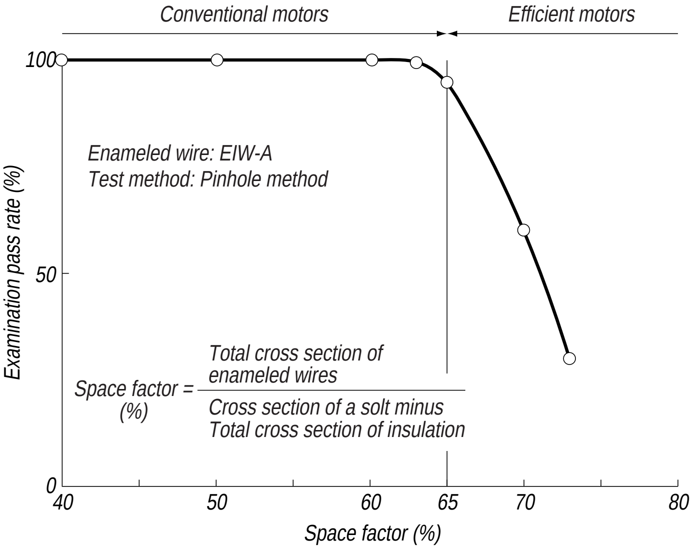


Fig. 2—Relationship between space factor and examination pass rate
The winding-examination pass rate of motor coils drops abruptly when the space factor exceeds 65%.

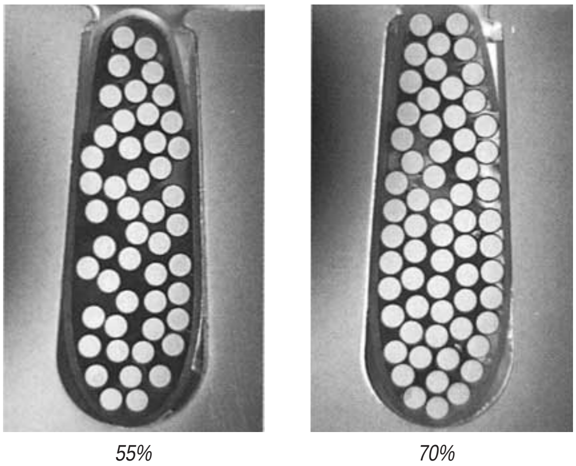

55%
70%

Fig. 3—Space factors of conventional (55%) and efficient (70%) motors
When enameled wires are wound closely together to achieve a 70% space factor, few gaps remain.

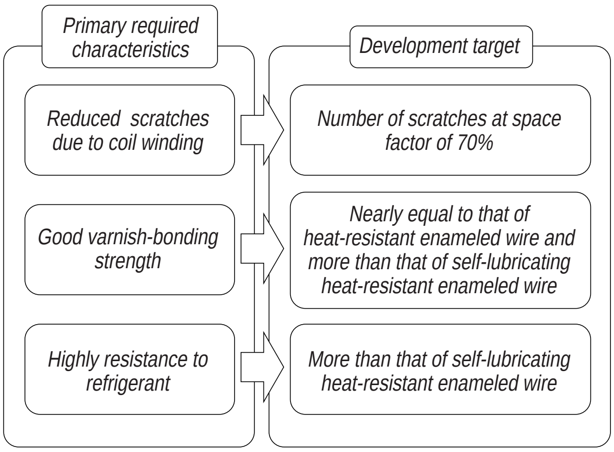


Fig. 4—Required characteristies
The primary required properties are reduced scratches due to coil winding, good varnish-bonding strength, and high resistance to refrigerant.

〔2〕REQUIRED CHARACTERISTICS AND DEVELOPMENT TARGETS

We focused on developing heat-resistant enameled wires for use in industrial F-class motors, vehicular motors, and refrigerator motors. We targeted a space factor of 70% or more in the motor coil.

The relationships between the primary required characteristics and the development targets for the enameled wires are summarized in **Fig. 4**.

(1) Reduced scratches due to coil winding

To achieve a higher space factor, a larger insertion force is needed. The result is more scratches on the wire insulation. We targeted the number of scratches to be 0.3 or less per coil slot. This is a general specification of motor manufacturers.

(2) Good varnish-bonding strength

Most electrical motors are varnished to prevent deterioration caused by electromagnetic vibration. The varnish-bonding strength of conventional self-lubricated enameled wires would not be enough for our enameled wire due to its superior surface lubricity. The use of a conventional varnish would shorten the motor lifetime. We thus targeted a varnish-bonding strength more than that of EIW-A (self-lubricating polyamide-imide/H class polyester-imide) wire and nearly that of AMW-XV (polyamide-imide/H class polyester-imide) wire.

(3) Highly resistant to refrigerant

We targeted a resistance to refrigerant equal to that of EIW-A wire in terms of blistering, dielectric breakdown, and extraction.

〔3〕PRIMARY FACTORS IN RELATION TO WINDING PROPERTIES AND FRICTION MECHANISM

The primary factors related to the coil-winding properties are conductor diameter, lubricity (resistance to abrasion), and softness. We analyzed the effect of these factors on the coil-insertion force, coil-formation force, and the number of scratches (pinhole method) by variance analysis. The space factor was 72%, and the coil-winding machine (**Fig. 5**) was an insertion type. As shown in **Table 1**, lubricity and resistance to abrasion plays the biggest role.

An SEM photograph of a scratched area and the scratch mechanism in coil winding are shown in **Fig. 6**. We can presume that the scratch shown was caused by wear of the insulation. Wear phenomena can be broadly divided into adhesive wear and abrasive wear. Shearing can be seen in the scratched area, so the wear is probably adhesive wear. The amount of adhesive wear is expressed as

$$\text{amount of adhesive wear} = (k \times P \times I)/(3 \times p) \quad \text{........................(1)}$$

where k is the coefficient of friction, P is the load, I is the wear length, and p is the flow pressure (hardness of material). We can reduce the amount of adhesive wear by reducing the coefficient of friction or increasing the flow pressure.

〔4〕SELF-LUBRICATING POLYAMIDE-IMIDE ENAMELED VARNISH

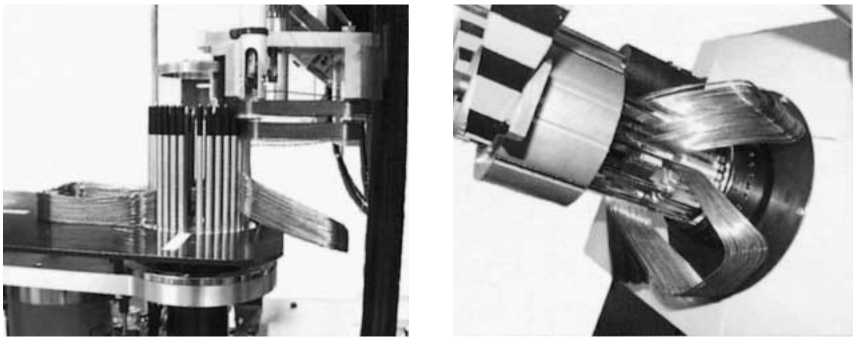
Generally, the lubricity of lubricating polyamide-imide enameled varnish used for self-lubricating heat-resistant enameled wires is improved by adding a small amount of lubricant (polyolefin system or fatty-acid-ester system) to enameled varnish. However, use of these enameled varnishes for enameled wires will result in many scratches at a space factor of 70% or more. The varnish-bonding strength will also

TABLE 1 EFFECT OF PRIMARY FACTORS ON COIL-WINDING PROPERTY

The factor having the largest effect is lubricity and resistance to abrasion.

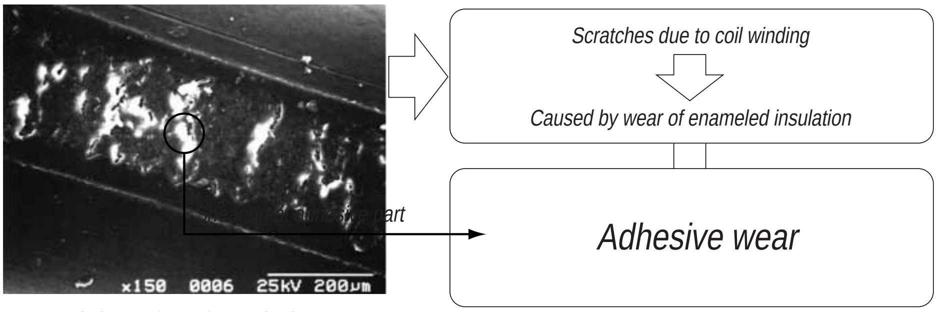
Factor	Coil-winding properties		
	Coil-insertion force	Coil-formation force	No. of scratches
Conductor diameter	—	—	*
Lubricity, resistance to abrasion	*	*	**
Softness (SEN)	*	*	*

* Significant at 5% critical rate ** Significant at 1% critical rate



Winding Insertion

Fig. 5—Insertion-type coil-winding machine
We analyzed the effects of three factors on the coil-winding properties.



Insulation surface of scratched area

Fig. 6—SEM photograph of scratched area
Shearing can be seen in the scratched area, so the wear is probably adhesive wear.

be inferior.

To improve the insulation mechanical strength and so on, we examined ways to improve lubricity, resin hardness, and varnish-bonding strength. As shown in **Fig. 7**, our objective was a self-lubricating material with superior hardness, responsiveness, and affinity to varnish. We developed a self-lubricating polyamide-imide enameled varnish that meets this objective.

〔5〕PROPERTIES OF SELF-LUBRICATING HEAT-RESISTANT ENAMELED WIRE

The properties of our KMK-20E self-lubricating heat-resistant enameled wire are.

5.1 General properties

As shown in **Table 2**, KMK-20E is superior to EIW-A and AMW-XV in terms of resistance to abrasion and coefficient of friction. Its resistance to abrasion is particularly better.

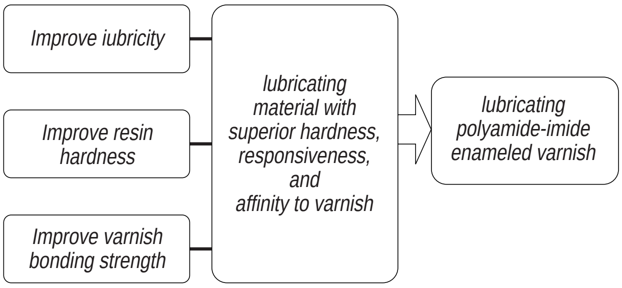


Fig. 7—*Development of lubricating polyamide-imide enameled varnish*
The lubricating polyamide-imide enameled material we developed has superior hardness, responsiveness, and affinity to varnish.

TABLE 2 GENERAL PROPERTIES (Ø0.7 mm, CLASS 0)

Item		KMK-20E	Present products		Notes
			EIW-A	AMW-XV	
Insulation thickness (mm)		0.042	0.042	0.042	—
Flexbility [winding]		2d, good	2d, good	2d, good	20% elongation d: conductor diameter
Dielectric breakdown (kV)		15.1	15.1	15.0	Twist pair method
Cut through (℃)		398	396	398	Temperature-raising method
Resistance to abrasion	Repeated (times)	406	226	202	—
	Unidirectional (N)	15.7	14.8	14.2	—
Coefficient of friction		0.048	0.050	0.120	Wire and Wire method

TABLE 3 VARNISH-BONDING STRENGTH (Ø0.7 mm, CLASS 0)

Varnish-treatment condition		Enameled wire	Bonding strength (N)
Type	Hardening condition		
Solvent-type epoxy system varnish for refrigerators	150℃×1.0 h + 150℃×3.5 h	KMK-20E	138
		EIW-A	106
		AMW-XV	149
Non-solvent type epoxy-ester system varnish for heat-resistance	120℃×0.5 h + 120℃×2.0 h	KMK-20E	105
		EIW-A	62
		AMW-XV	123

TABLE 4 RESISTANCE TO REFRIGERANT (Ø0.7 mm, CLASS 0)

Properties		KMK-20E	Present products		Notes
			EIW-A	AMW-XV	
Resistance to R-22 refrigerant [125℃×7 days]	No blistering (℃)	140	140	140	Hitachi method R-22/refregerant oil = 700 g / 700 g
	Remaining rete of dielectric breakdown (%)	102	102	103	
Extraction with R-22 refrigerant [150℃×24 h, extraction rate (%)]		0.048	0.050	0.120	JIS C 3003

TABLE 5 PROPERTIES OF REFRIGERANT OIL

Item			Oil with enameled wire	Oil only	Notes
Conbination	Enameled wire [KMK-20E]		1,000 g	—	Heat condition: 180℃×24 h
	Refrigerant oil		450 g	450 g	
	R-22		1,000 g	1,000 g	
Properties of refrigerant oil	Viscosity (mm^2/s)	40℃	29.27	29.20	
		100℃	4.28	4.28	
	Total acid (mg KOH/g)		0.01	0.01	Mass of KOH for nuetralization
	Floc point (℃)		−56	−58	Eduction temperature
	Pour point (℃)		−40	−40	No-flow temperature

5.2 Varnish-bonding strength

As shown in **Table 3**, the varnish bonding strength of KMK-20E is 30 to 70% greater than that of EIW-A for both solvent-type epoxy system varnish for refrigerators and non-solvent type epoxy-ester system varnish for heat-resistance. It is close to that of AMW-XV.

5.3 Resistance to refrigerant

As shown in **Table 4**, the resistance of KMK-20E to R-22 refrigerant in terms of blistering, dielectric breakdown, and extraction is almost equal to that of EIW-A and AMW-XV.

As shown in **Table 5**, the properties of refrigerant oil heated with enameled wire at 180℃ for 24 hours in a pressure-tight vessel are almost equal to those of refrigerant oil heated alone.

Consequently, the resistance of KMK-20E to refrigerant is of no concern.

5.4 Coil-winding property

The relationship between the space factor and the insertion force is shown in **Fig. 8**; that between the space factor and the number of scratches is shown in **Fig. 9**.

The coil-insertion force of KMK-20E is smaller than that of EIW-A, and as the space factor becomes larger, the difference becomes bigger. The number of scratches with KMK-20E is much less than that with EIW-A. These results indicate that KMK-20E is applicable under large space-factor conditions, around 74%.

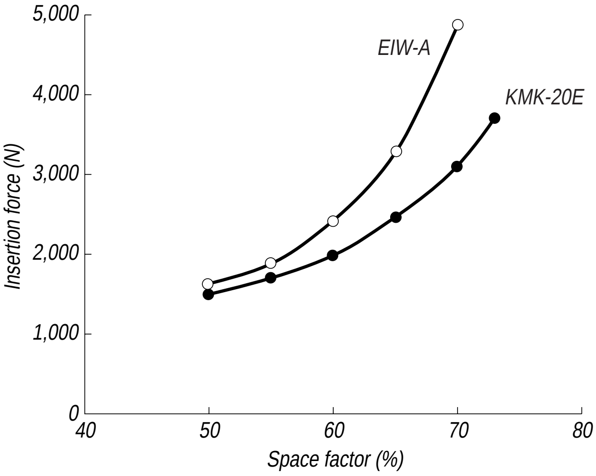


Fig. 8—Relationship between space factor and insertion force
The coil-insertion force of KMK-20E is smaller than that of EIW-A, and as the space factor becomes larger, the difference becomes bigger.

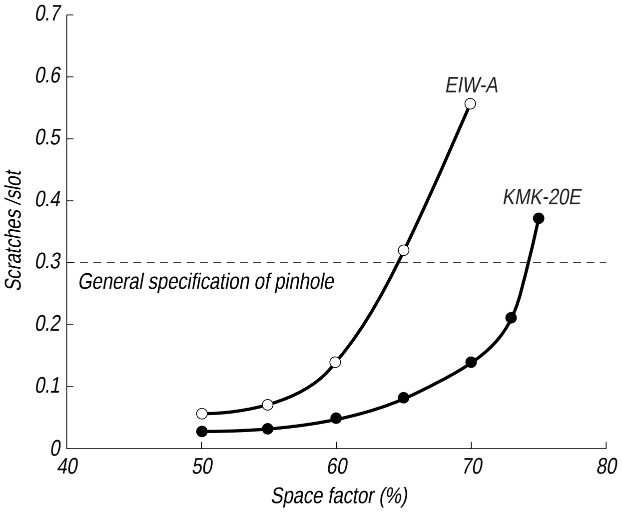


Fig. 9—Relationship between space factor and number of scratches
The number of scratches with KMK-20E is much less than that with EIW-A at the same space factor. KMK-20E is thus applicable under large space-factor conditions, around 74%.

〔6〕CONCLUSION

To help meet the need for more efficient electrical motors, we have developed and manufactured a self-lubricating heat-resistant enameled wire (KMK-20E) that can be used when the space factor is 70% or more. This wire has superior lubricity and varnish-bonding strength compared to conventional enameled wires, and can thus improve the reliability of motor insulating system.

Many motor manufacturers are developing more efficient motors. We plan to develop enameled wires that can be applied to these motors.

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