Development of Magnet Wires Having Excellent Windability

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ABSTRACT In recent years there is an increasing demand for enhanced windability of magnet wires used in household electrical appliances and automobile electrical components. The reasons are that it is becoming more important to make motors and transformers used in these fields more powerful and reduced in cost than ever before, and to this end, winding processes have actively been speeded up and automated, and that the slot fill has been improved to enhance the performance of these products. Under such circumstances, winding damage given to magnet wires has increased, causing damage to insulation films.

To prevent such damage, magnet wires offering surface lubrication have heretofore been developed by applying wax to the surface of magnet wires and making the surface self-lubricant. However, these techniques are not enough to meet the requirements for the windability of magnet wires. From a viewpoint different from conventional techniques, we have developed the technique of improving the adhesion between the conductor and the insulation film and succeeded in producing new magnet wires enhancing the windability greatly. This paper describes the development and properties of the new magnet wires, as well as their applications.

1. INTRODUCTION

In recent years labor savings and rationalization are in process in the manufacture of electrical equipment, and coil winding processes for motors and transformers have also been actively speeded up and automated. However, when an automatic winding machine is used, the possibility of doing damage to the insulation films of magnet wires is increased because the wires are wound under the conditions of bending, friction together with strong tension, thereby decreasing the electrical reliability of the coils themselves. In coil forming, it is desirable to increase the slot fill (percentage of the volume of magnet wires in the total volume of equipment) as much as possible, which is very effective in the economy and workability of the whole equipment. Increasing the slot fill of coils requires applying increased tension to magnet wires to wind the coils closely. However, when the stator slot in the motor is forcibly filled with more magnet wires in the winding process, it may result in damaged insulation films. If such damage occurs to the insulation films, there is a problem of poor layer insulation and poor grounding. This requires a high degree of windability for the magnet wires used in coils. It is thought that lubrication and abrasion resistance of the surface of magnet wires greatly influence windability. The method of imparting surface lubrication has heretofore been studied by applying wax, oil or the like to the surface of magnet wires and curing the surface overcoated with paint added with polyolefine.

However, it cannot be said that such techniques are enough to reach adequate solutions under the present condition where winding processes have increasingly been speeded up and automated.

We have recently developed magnet wires offering excellent windability than ever before to meet these requirements. This paper describes the properties and effects of the new magnet wires, in which the adhesion between the conductor and the insulation film (often called simply "adhesion" hereafter) is improved more than ever before.

2. CONCEPT OF DEVELOPMENT (TECHNIQUES OF IMPROVING WINDABILITY)

Three techniques can be used to enhance the windability of magnet wires. Figure 1 shows the outline.

The first is to increase the strength of insulation films, which makes it hard to get damaged because they resist better external factors including wear. For example, magnet wires with overcoat of polyamideimide resin containing thermoplastics belong to this category. [1)]

The second is to modify the condition of the surface of insulation films. For example, when lubrication is imparted to the surface of insulation films, the lubrication prevents damage to the insulation films. The techniques of enhancing lubrication include the method of applying wax, oil or the like and that of self-lubrication in which the surface is overcoated with resin containing polyolefine. The latter, in particular, offers good slipping ability and abrasion resistant properties, thus coping with high speed winding and

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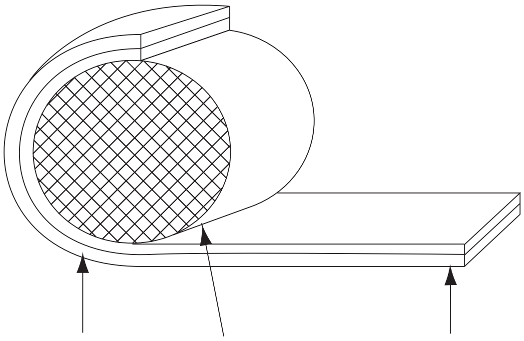

Figure 1 Concept of the technique of improving windability

automatic winding.

The third is a technique we have recently approached, and it is intended to improve the adhesion between insulation film and conductor. The technique is aimed at preventing the insulation films from being peeled off readily from the conductor thereby enhancing windability.

To be more specific regarding the third technique in particular, the techniques of improving the adhesion include the technique of treating conductor surface and that of modifying resin.

For the conductor surface treatment, for example, it is already known that the treatment is feasible by applying imidazole or the like to the conductor surface. The technique has an advantage of eliminating the need for resin modification, while it poses problems of increasing manufacturing processes and of doing precise coating longitudinally, which is difficult to be controlled accurately.

For the resin modification, it should be noted that there is a difference in the level of adhesion depending on the material of insulation films, i.e., decreasing in the order of polyester resin, polyesterimide resin, and polyamideimide. The difference probably results from the abundance of terminal groups with a high polarity like -OH group contained in the resin. Consequently, improving the adhesion requires introducing polar groups having high interaction with the conductor into resin. Though adhesion may improve with this method, concerns are raised about the changes in resin properties.

We introduced polyamideimide (hereinafter referred to as "(AI/) HPE") magnet wires using THEIC (Tris-hydroxyethyl Isocyanurate) modified class H polyester (hereinafter referred to as "HPE") in the previous report. [2)]

These magnet wires are improved more than polyesterimide resin in the adhesion between conductor and insulation film. We succeeded further in improving the adhesion by resin modification.

In the present study, by combination of these techniques of improving windability, we achieved a high degree of windability exceeding the magnet wires that were previously studied, that is, the wires with enhanced surface lubrication only.

Table 1 Insulation film structure of magnet wires

	AI/EI	AI/HPE	N-AI/HPE
Under-coat	Polyesterimide	H class polyester (conventional)	H class polyester (developed)
Over-coat	Polyamideimide	Polyamideimide	Polyamideimide

Table 2 General Properties of magnet wires

	AI/EI	AI/HPE	N-AI/HPE
Conductor diameter (mm)	0.85	0.85	0.85
Insulation thickness (μm)	30	30	30
Breakdown voltage (kV)	10.2	10.1	10.5
Cut-through (°C)	420	420	420
NEMA heat shock 220°C x 30 min	1D OK	1D OK	1D OK
Flexibility 220°C x 6 hr	1D OK	1D OK	1D OK

3. PROPERTIES OF DEVELOPED MAGNET WIRES

We have evaluated three types of magnet wires this time. Table 1 gives the structure of the insulation layers of the magnet wires including N-AI/HPE, the wire newly developed, and Table 2 their general properties. It is seen that all magnet wires are nearly equivalent to one another in terms of general properties.

The following are the evaluation and examination results of the enhancement in the windability of magnet wires, with adhesion in focus in particular.

3.1 Adhesion

There are several methods of evaluating adhesion.

A peel twist test is a simple evaluation test among the methods that have been used. With this method, one end of a magnet wire having a longitudinal slit made with a cutter is fixed, and the wire is horizontally stretched to have a gauge length of 150 mm and a load of 500 grams. And the other end is twisted 360 degree to count the number of twists until the insulation film peels off to bare the conductor. This method of evaluation serves somewhat to give a measure of the strength of adhesion, but the number of peel twists may vary depending on the flexibility of the insulation film itself.

Therefore, we tried a new method to directly evaluate the adhesion force between the conductor and the insulation film. First, a magnet wire was crushed at a certain compression ratio, and two parallel slits were longitudinally made at an interval of about 0.6 mm. And one end of the slit insulation film was peeled off from the conductor to measure the tension when the film was peeled off at a speed of 2 mm/min in the direction of 90 degrees with respect to the wire axis.

The peel twist tests in Figure 2 reveal that the AI/HPE magnet wire, following the N-AI/HPE wire, has more numbers of twists before the insulation film peels off to bare the conductor than AI/EI.

Next, Figure 3 shows the results achieved by the new

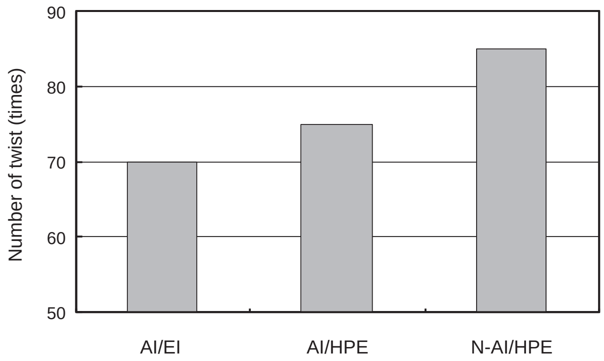

Figure 2 Peel-twist test results

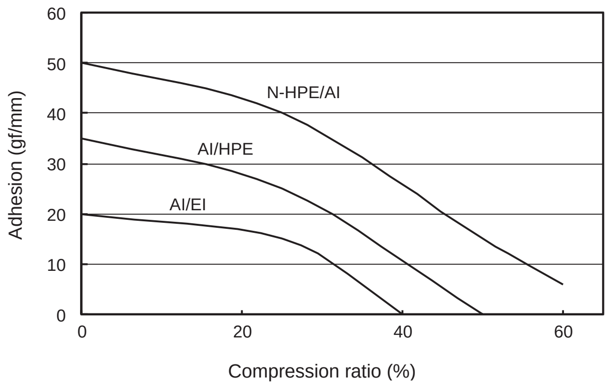

Figure 3 Measurement results of adhesion force between conductor and film

method of evaluating adhesion described above. The adhesion force given on the vertical axis refers to the peeling force as a magnet wire is stamped in a rectangular cross-section with a certain compression ratio. The compression ratio given on the horizontal axis indicates the ratio at which magnet wires are compressed, that is, the displacement during the stamping. This method was adopted to simulate actual wire winding, during which wires are often deformed considerably. A compression ratio of 60% was used as a critical value. It was observed that the adhesion force tended to decrease with increase in compression ratio. N-AI/HPE shows the same tendency as for the peel twist test, and it is higher than AI/EI and AI/HPE magnet wires in terms of adhesion force. Special attention should be paid to the fact that the adhesion force of N-AI/HPE magnet wires is as high as 6 gf/mm even after working at a compression ratio of 60%, higher than that of other wires.

The above two adhesion evaluations demonstrate that N-AI/HPE magnet wires are remarkably improved in the adhesion as compared with conventional AI/HPE magnet wires.

3.2 Windability

Next, we carried out unidirectional abrasion tests, repeated scrape tests and NEMA windability tests to verify the effects of the level of adhesion on windability. Table 3 gives the results.

Table 3 Windability properties of magnet wires

	AI/EI	AI/HPE	N-AI/HPE
Unidirectional abrasion (N)	15.2	16.2	18.6
Repeated scrape (times)	200	200	205
NEMA windability test (strokes)	23	26	30

In the unidirectional tests, a piano wire was moved in the direction of a magnet wire while a load was applied on the piano wire intersecting perpendicularly the magnet wire, and the load was varied at a given rate to measure the load when the insulation film of the magnet wire broke to bare the conductor.

In the repeated scrape tests, repeated scrapes were implemented with a given load applied to count the number of times until the conductor was bared.

In the NEMA windability tests, one turn of magnet wire was wound around a mandrel, and the mandrel was reciprocated in the longitudinal direction of the magnet wire with a tension applied to the wire. A voltage of 1,500 volts was applied between the magnet wire and the mandrel to count the number of strokes before three shorted points or more were detected.

The unidirectional abrasion tests show that N-AI/HPE magnet wires offer a higher value of abrasion load than AI/EI and AI/HPE magnet wires, indicating that the N-AI/HPE magnet wire is considered the best.

The repeated scrape tests revealed that N-AI/HPE magnet wires were almost equivalent to AI/EI and AI/HPE magnet wires and that there was no significant difference in the number of abrasion times.

For the NEMA windability tests, N-AI/HPE magnet wires offer more numbers of strokes than AI/EI and AI/HPE magnet wires, indicating that the N-AI/HPE magnet wire is considered the best.

We could thus verify that the N-AI/HPE magnet wire with improved adhesion between the conductor and the insulation film showed an improvement effect in the unidirectional abrasion tests and windability tests and that the windability was enhanced.

3.3 Discussion (Adhesion and Windability)

Since an enhancement in windability was observed by improving the adhesion as mentioned above, we gave consideration to knowing its contribution or analyzing its factor.

First, in order to make the factor clear, we decided to study how adhesion and lubrication interact with each other. We used three types of wires with different levels of adhesion, i.e., increasing in the order of AI/EI, AI/HPE, and N-AI/HPE; and four levels of lubrication expressed by static friction coefficient: non-lubricated (non-treated) = 0.13, wax-treated = 0.08, self-lubricated upper polyamideimide resin = 0.03, and the same = 0.05.

Figure 4 shows the relation with unidirectional abrasion. Studies reveal that an effect resulting from the enhancement in surface lubrication is not shown, but that an effect resulting from the enhancement in adhesion is obvious. It is apparent that the N-AI/HPE magnet wire is improved in

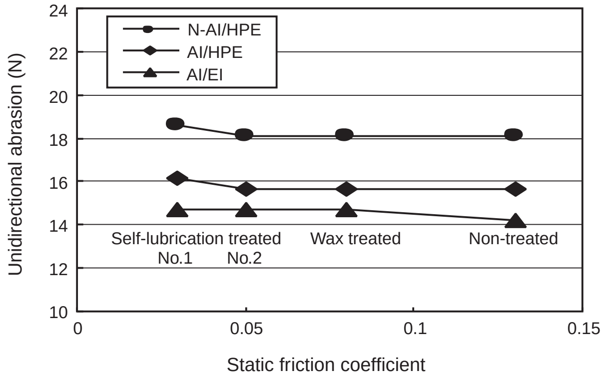

Figure 4 **Effect of lubrication and adhesion on unidirectional abrasion properties**

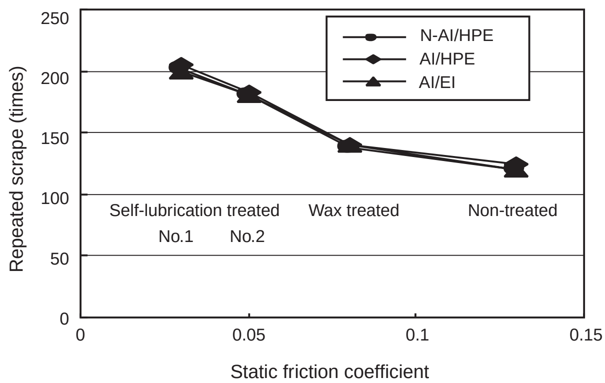

Figure 5 **Effect of lubrication and adhesion on repeated scrape properties**

particular. This is probably because the adhesion between conductor and insulation film has a great effect when, as in the case of the unidirectional test, such a great external force as to peel off the insulation film is used.

Next, Figure 5 shows the relation with repeated scrapes. Studies reveal that an effect resulting from the enhancement in surface lubrication is noticeably shown in contrast to unidirectional abrasion, but that there is no effect resulting from the improvement in adhesion and that there is no difference between improved magnet wires and conventional magnet wires. This is probably because, in view of the fact that the repeated scrape test is based on repeated scrapes under a relatively light load, only the surface treatment of magnet wires had an effect.

Figure 6 shows the relation with NEMA windability tests. Studies reveal that an effect resulting from the enhancement in surface lubrication is not shown, but that an effect resulting from the enhancement in adhesion is obvious, and the same results as for unidirectional abrasion were obtained.

During the windability test, the adhesion force between the conductor and the insulation film seems to decrease little by little, and thus the insulation film becomes abnormally nonuniform. This causes defects such as cracks in the portion where the insulation film is extraordinarily elongated. The N-AI/HPE magnet wire offers a smaller degree of decreased adhesion than the AI/HPE magnet wire, which may result in the increased number of strokes.

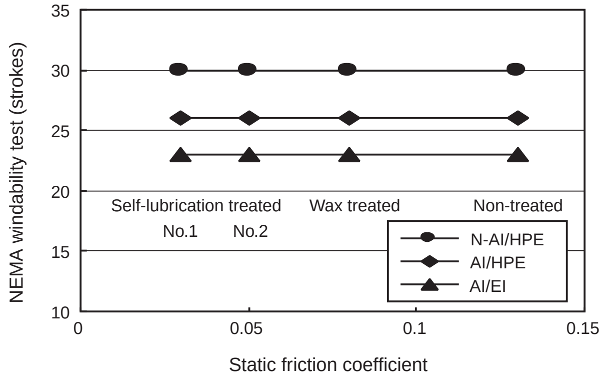

Figure 6 **Effect of lubrication and adhesion on NEMA windability test**

Table 4 **Effect of various factors on windability properties**

	Surface lubrication	Adhesion
Unidirectional abrasion	Not effective	Effective
Repeated scrape	Effective	Not effective
NEMA windability	Not effective	Effective

Table 4 presents the relation between windability and the factors thus obtained. In the past, surface lubrication has been aggressively studied as a technique of improving windability. The enhancement in lubrication permits reducing damage to the insulation film caused by contact between magnet wires or with the coil slot. As a result, it is assumed, damage to the insulation film can probably be prevented. However, when a great external force that cannot be reduced by surface lubrication only --such as is the case with unidirectional abrasion test or windability test-- is applied, it is presumed that the enhancement in the adhesion between the conductor and the film becomes effective in preventing damage to the insulation film. Windability exceeding conventional magnet wires will probably be achieved by a combination of the enhancement in the adhesion and the enhancement in the lubrication of the surface of a magnet wire.

3.4 Refrigerant Properties

The AI/HPE magnet wire we have recently evaluated has many applications including refrigerators and air conditioners as a refrigerant-resistant wire. In these applications, the magnet wire is used as is immersed in refrigerant. We also evaluated the reliability of the magnet wire used in refrigerant.

A magnet wire was immersed in refrigerant R22 used mostly in air conditioners and refrigerant R410A beginning to be used as an alternative refrigerant at 150°C for 1,000 hours to evaluate its blister resistance.

When a magnet wire is immersed in refrigerant, taken out and then rapidly heated up to a given temperature, blister occurs on the surface of the wire. Blister resistance means the degree of resistance to blister occurrence. Table 5 gives the evaluation results.

Comparison of AI/HPE and N-AI/HPE magnet wires reveals that both magnet wires are provided with high

Table 5 Refrigerant resistance properties

		AI/HPE	N-AI/HPE
R22+oil (150°C x 1000 hr) Blister	120°C	Good	Good
	140°C	Good	Good
	160°C	Good	Good
R410A+oil (150°C x 1000 hr) Blister	120°C	Good	Good
	140°C	Good	Good
	160°C	Slight foaming	Slight foaming

resistance to blistering in the refrigerant R22 and that there is no difference recognized in the blister resistance between the two.

The same results were obtained also with the new refrigerant R410A.

4. CONCLUSION

1) The newly developed magnet wire (N-AI/HPE) is enhanced in adhesion between the conductor and the insulation films as compared with the conventional magnet wire (AI/HPE). This results in the enhanced properties of unidirectional abrasion and NEMA windability, thereby providing high windability.
2) It was also found that the requirements for windability becoming more and more strict could be met by a combination of the developed magnet wire and the surface treatment offering high lubrication.
3) Magnet wires using the technique of improving adhesion are equivalent to conventional magnet wires in other basic properties including refrigerant resistance, and thus application to the same areas as before will be possible.

REFERENCES

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