Fabrication of chromium-free coating solution with nano-sized silica particle for high insulation resistance on the surface of non-oriented electrical steel

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ABSTRACT

This study was investigated the effect of nano-sized silica particle on the insulation resistance of non-oriented electrical steel. Several kinds of nano-sized colloidal silica were added to the non-chromium coating solution consisted of metal phosphate and polyester resin. To explain the insulation resistance mechanism, the series micro-dielectric effect is introduced. In well-dispersed nano-sized particle in the coating layer, the successive micro-dielectric results in the electrical insulation resistance. Franklin insulation tester was employed to determine the electrical resistance associated with the conduction of an electrical current. It is found that the size and solid content of silica particle were strongly influenced on the insulation resistance of electrical steel sheet.

Keywords: chromium-free coating, nano-sized colloidal silica, insulation resistance, series micro-dielectric effect

1 INTRODUCTION

Electrical steels are used in the magnetic cores of such machines as motors, generators and transformers. Intensive effects have been directed at developing improved steels with lower iron loss for use in energy efficient machines. The eddy current loss component of the core can be reduced by use of insulating coatings to ensure that the eddy current is restricted to individual laminations. The selection of the most suitable coating solution for a specific application has to be made with reference to the insulation resistance, punchability, corrosion resistance properties, weldability, heat resistance, stacking factor, chemical resistance, burn-out characteristics, resistance to compression, coating thickness, surface roughness and scratch resistance properties.

A coating solution which forms an insulation coating of a non-oriented electrical steel sheet generally classified into three types. That is an inorganic coating solution, an organic coating solution and an organic-inorganic composite coating solution.

The inorganic coating solution (So called C-4 type) is composed mainly of inorganic materials such as phosphate which enables the formation of a coating film having high heat resistance, weldability, and layering properties. However, due to the high hardness of the insulation coating film, a mold of punching machine is more quickly damaged than when using a coating film containing an organic material. Consequently, the inorganic coating solution is not desirable from the aspect of punching processability.

The organic coating solution (So called C-3 type) is composed mainly of an organic material and is very superior in terms of punchability. Even when the thickness of the film is increased, adherence is good, and thus the organic coating solution is chiefly used for large iron cores requiring interlayer insulating properties. However, the weldability of the organic coating film is not good because resin-decomposing gas is generated upon welding, and organic coatings not withstand stress relief annealing (SRA).

For this reason, in the interest of improving heat resistance and insulation properties, there has been developed an organic-inorganic combination coating system (So called C-5, C-6 type) using both an organic material and an inorganic material. A phosphate or chromate is mainly used for the inorganic materials. In the case of a coating film formed using such an insulation coating solution, heat resistance, which is characteristic of the inorganic material, and the lubrication effects of the organic material are realized at the same time, thus realizing a beautiful surface appearance.

The method of forming an insulation coating film by using an organic-inorganic coating is well-known. In the case where chromate is used, a hydrogen bond is formed between chromate and the Fe oxide layer of a base layer, thus attaining excellent coating properties, including adherence and punchability, and furthermore, good coating properties may be obtained even after SRA. However, due to the composition of such a conventional coating solution essentially contains chromium oxide, unfavorable effects on the human health and environmental problems are caused. Attributable to the above problems, the use of heavy metals, including hexavalent chromium, is limited under the current strict control of environmental restrictions such as RoHS (restriction of the use of hazardous substances) and REACH (Registration, Evaluation, Authorization and restriction of Chemicals) among countries of EU.

Accordingly, in this study, the various types of nano-sized colloidal silica are applied to improve the insulation property of non-oriented electrical steel. The Franklin tester (ASTM A717) was used to evaluate the insulation properties of coated samples. The mechanism of insulation resistance on the surface of the electrical steel was investigated. The effect of nano-sized colloidal silica, especially for the particle size and solid content of silica, on the insulation properties is elucidated in detail. Here basic
coating solution is the mixture of metal phosphate and polymer resin.

2 EXPERIMENTAL PROCEDURE

A 50A1300 JIS grade steel sheet produced by POSCO was used for the experiment samples. A bar coater (#4) was utilized to coat samples having 50mm in width and 150mm in length. Coating solutions were prepared with the following compositions: Metal phosphate (Aluminum phosphate, Al(H₂PO₄)₃ and zinc phosphate, Zn(H₂PO₄)₂), emulsion-type polyester resin and 4 different size of colloidal silica. Here the size range of colloidal silica is between 7nm and 88 nm, and the range of solid content of silica in the coating solution is up to 18.6 wt. %. The detail properties of colloidal silica are showed in table 1.

<table>
<thead>
<tr>
<th>Size</th>
<th>Solid content</th>
<th>Shape</th>
<th>Base</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 nm</td>
<td>31 wt. %</td>
<td>Spherical</td>
<td>H₂O</td>
</tr>
<tr>
<td>15 nm</td>
<td>31 wt. %</td>
<td>Spherical</td>
<td>H₂O</td>
</tr>
<tr>
<td>45 nm</td>
<td>31 wt. %</td>
<td>Spherical</td>
<td>H₂O</td>
</tr>
<tr>
<td>88 nm</td>
<td>30.5 wt. %</td>
<td>Spherical</td>
<td>H₂O</td>
</tr>
</tbody>
</table>

Table 1 : Properties of colloidal silica

The prepared electrical steel samples are coated by coating solution with the nano-sized colloidal silica. Coated samples are baked at 650 °C radiant tube furnace for 20 seconds. The Franklin insulation tester was employed in order to determine the electrical resistance associated with the conduction of an electrical current through the surface of the samples. SEM&FIB, EDS, EPMA and GDS techniques are utilized to analyze the coating thickness and behavior of nano-sized silica in coating layer.

3 RESULT AND DISCUSSION

Electrical steels used for motor, transformer and generator applications are usually coated with an insulation coating in order to improve the performance of the electrical steel in terms of reduced iron loss (including eddy current loss), punching and welding properties and corrosion resistance. In order to minimize iron loss in proportion to the square of the thickness of the electrical steel, an insulation coating is formed on both sides of surfaces. Usually the eddy current loss, $P_{ec}$ can express as following form (equation 1). Here $B_o$, $t$, $f$, and $\rho$ are maximum permeability, steel thickness, frequency and density, respectively.

$$P_{ec} = \frac{10^{-9} \pi^2 B_o^2 \cdot t^2 \cdot f^2}{6 \cdot \rho}$$

An equation 2 shows the relationship between the insulation resistance, $r$ and the increasing rate of iron loss by eddy current loss, $C (%)$. This equation means that the higher insulation resistance, the smaller increasing rate of iron loss. Increasing insulation resistance leads to increasing the efficiency of electrical machines. Here, $K$, $f$, $\rho$, $B_o$, $a$, $t$, and $W_o$ are stacking factor, frequency, density, permeability, width of electrical steel, thickness and iron loss at standard $f$ and $B_o$, respectively.

$$C(\%) = \frac{1.65 \cdot f \cdot B_o^2 \cdot a^2 \cdot k \cdot t}{\rho \cdot W_o \cdot r} \times 10^{-1}$$

A number of papers already explained the effect of nano-sized particle on the insulation properties. These papers are described that insulation property is strongly affected by the barrier effects of the coating layer. Here a barrier effect is increased by increasing the amount of colloidal silica.

To confirm the behavior of nano-sized silica on the surface and in the layer of coating, a various analysis techniques are utilized. Here the coating solution is composed of 40 wt. % of metal phosphate, 40 wt. % of polyester resin and 20 wt. % of colloidal silica. Solid content and particle size of the colloidal silica are 31 wt. % and 45nm, respectively. Figure 1 shows the SEM image (a), EDS mapping image (b) and EPMA analysis pick (c) of the coating surface, respectively.

Figure 1 : the SEM image (a), EPMA and EDS spectrum analysis of coating surface.

From the SEM (Scanning electron microscope) image, EPMA (Electron Probe Micro Analyzer) mapping image and EDS (Energy dispersive spectroscopy) analysis pick, coated samples have macroscopically very smooth surface which surface roughness is approximately 0.2–0.3 μm. Furthermore, it can be clearly confirmed the presence of the silica particle (SiO₂) which is well-dispersed on the surface of coating.

Figure 2 shows the cross section of coating layer fabricated by FIB (Focused Ion Beam) & SEM techniques
(a) and GDS (Glow Discharge Spectroscopy) analysis graphic (b).

Figure 2: Cross section of coating layer (a) and GDS analysis graphic (b).

As a result of SEM image and GDS analysis graphic, the structure of the coating layer was formed compactly without cracking, and the silica particle is well-distributed in the layer of coating. Here, the coating thickness is approximately 0.7 μm.

As already noted above, in order to improve the barrier effect (so-called insulation resistance), the colloidal silica is added to the coating solution. In these papers, the size and amount of nano-sized particle are described as the main factor of insulation properties. However, no one has considered the relationship between the barrier effect and the electric intensification (especially current). In this paper, a series micro-dielectric effect is introduced to explain the insulation mechanism of coating surface.

Figure 3: Schematic sketch of series micro-dielectric effect model.

Figure 3 illustrates the schematic sketch of series micro-dielectric effect, which explains the electric field intensifying due to the conductive nano-sized particles in coating layer. Under the DC voltage, separations of positive and negative charges within the coating layer occur respectively at the top and bottom surface. As a result, local electric intensification is generated between the particle-to-particle, particle-to-resin (+ phosphate) and particle-to-electrode gap. This means that the nano-sized particle acted as the current barrier. Therefore, successive micro-dielectric in the coating layer results in the electrical insulation resistance. As a result of successive micro-discharge, the electrical insulation resistance will be increased within well-dispersed nano-sized particle on the coating layer.

The Franklin test (conditions: 300psi, 1000mA, 0.5V) was employed to coated samples in order to determine the electrical resistance associated with the conduction of an electrical current through the surface of the samples. Normally main parameter of the insulation properties in filed of electrical steel are as follows: component of coating solution, coating thickness, structure of coating layer and external factors (pressure and temperature at testing point). However, in this study, the size and amount of colloidal silica as a factor of the coating component are only considered. Here, metal phosphate and polyester resin are basic coating component.

First of all, it is investigated the effect of silica size on the insulation property. Figure 4 shows the current insulation at 4 different sizes of silica which is chosen to 7, 15, 45 and 88 nm. All other parameters are kept constant: coating thickness of 0.7 μm and solid content of silica particle of 6.2 wt. %. As shown in the Figure 4, under basic coating component consisting metal phosphate and polyester resin, the value of insulation current is about 100 mA. This means that 900mA of current are flowing through the surface between the contact of Franklin tester and the base metal (electrical steel). However, if the colloidal silica is added to coating solution, the value of insulation current is increased with decreasing the size of silica particle. At the 7 nm of silica size, the value of insulation current is approximately 500 mA in average of 5 sheets. This means that here 500 mA of current is restricted by surface of coating entrapped the silica particle. It can be explained as series micro-dielectric effect. As explained before, the micro-dielectric is generated between the particle-to-particle, particle-to-resin (+ phosphate) and particle-to-electrode gap in coating layer. As increasing total surface area of silica particle, the effect of micro-dielectric should be increased. Therefore, the insulation current is increased among well-dispersed silica particles.

Figure 4: Current insulation vs. Particle size of silica at the same coating thickness.

Figure 5 shows the relationship between the current insulation and the solid content of silica at particle size of
15nm and coating thickness of 0.7 nm. As mentioned above, the series micro-dielectric effect rises with increasing solid content of silica, because total surface area of silica increases rapidly. The insulation current is, however, only increased up to 9.3 wt% of silica and than the insulation current begins to decrease. The reason for the mentioned behavior is that the aggregation and cohesion phenomena should be occurred at high amount of silica particle. Figure 6 illustrates the cross section of coating layer by SEM photos at high amount of silica (12.4 wt. % of solid content). It can clearly be found that the silica particle has a tendency to aggregate each other. Therefore, at such a high amount of silica particle should be restricted the micro-dielectric effect.

Figure 5 : Current insulation vs. solid content of silica at the same coating thickness.

Figure 6 : Aggregation phenomena of silica on the coating layer.

4 CONCLUSION

In this study, the effect of nano-sized silica particle on the insulation resistance of non-oriented electrical steel is investigated. Several kind of nano-sized colloidal silica was added to coating solution which consisted of metal phosphate and polyester resin. With a various analysis techniques, it is clearly analyzed that nano-sized silica particles are well-dispersed in the layer of coating.

The series micro-dielectric effect is introduced to explain the insulation resistance mechanism. In well-dispersed nano-sized particles in the coating layer, successive micro-dielectric results in the electrical insulation resistance. As a result of successive micro discharge, electrical insulation resistance will be increased.

As an experimental result, the insulation resistance is increased by decreasing the particle size of silica. Moreover, it is increased by increasing solid content of silica. It is, however, only increased to a certain extent of solid content and than it begins to decrease because of an aggregation and cohesion phenomena in the coating layer.

REFERENCES