Study on Electrolytic Re-insulation Grinding of Soft Magnetic Powder Cores

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Soft magnetic powder cores (SMPCs) are used for electromagnetic conversion coils which are essential parts in automotive, home appliance, and electronics industries. These cores, manufactured by compacting pure iron powder covered with an insulation layer, are distinguished by the high electromagnetic conversion efficiency. However, their electromagnetic conversion efficiency drastically decreases when they are subjected to conventional finishing processes. This is directly attributable to conductive layers formed on the finished surfaces, which significantly reduce the electrical resistance of material surfaces. As a solution to this problem, we developed an electrolytic re-insulation grinding method that finishes materials while applying a current between the material and the grinding wheel. This method regenerates the insulation properties of SMPCs through the electrolytic removal of conductive layers formed during finishing, thereby improving electrical resistance. This development enables the finishing of SMPCs without compromising their electromagnetic conversion efficiency.

Keywords: electrolytic re-insulation grinding, soft magnet powder cores, ELID, electrical resistance, insulation layer, iron loss

1. Introduction

In order to realize a society with a reduced carbon footprint, the shift towards electric automobiles, the development of home appliances and electronics focusing on lower levels of power consumption, and the utilization of clean energy is accelerating. Among the components at the core of these products are coils for electromagnetic conversion, which consist of an iron core and winding. Products employing coils for electromagnetic conversion include electromagnetic motors and voltage converter transformers [(1)-(3)]. Recently, soft magnetic powder cores (SMPCs) have been drawing attention as materials for iron cores mentioned above [(4)]. These cores are manufactured by compacting pure iron powder covered with an insulation layer. SMPCs have a high degree of electrical resistance in comparison with conventional electromagnetic laminated steels and, in particular, exhibit superior electromagnetic conversion efficiencies in the high frequency range. However, to keep up with today's growing tendency towards enhanced precision and downsizing of devices, SMPCs are also required to be finished into more complicated shapes while maintaining high dimensional accuracy. As finishing methods for SMPCs, cutting, grinding, and other machining methods have been proposed [(5)]. However, the electromagnetic conversion efficiencies of SMPCs significantly decrease when such conventional finishing methods are applied to them. This is probably due to significant decreases in the electrical resistance of material surfaces as a result of (1) the removal of insulation layers (one of the features of SMPCs) from finished surfaces, and (2) the formation of conductive layers with low electrical resistance by pure iron powder particles that undergo plastic deformation under processing stresses and become conductive with adjoining iron particles. Electrical resistance is an important characteristic for satisfactory electromagnetic conversion efficiencies in the high frequency range in particular, and it is therefore necessary to develop a finishing method that does not cause decreases in electrical resistance.

This paper details the electrolytic re-insulation grinding (ERiG) method we developed, which is capable of finishing SMPCs without compromising electrical resistance. This finishing method makes use of electrolytic in-process dressing (ELID) grinding that can provide material surfaces with mirror finishes very efficiently [(6)], and this method was applied to some of surface modifications [(7),(8)]. More specifically, this finishing method embodies the features of electrolytically removing the conductive layer formed on the finished surface of a SMPC by applying a current between the surface and the grinding wheel and, at the same time, re-forming a nonconductive layer in place of the removed insulation layer. The authors confirmed the effect of this finishing method through a comparison between this method and conventional grinding methods, and evaluated the electrical resistance and the iron loss characteristic, which are the indicators of electromagnetic conversion efficiency of SMPCs subjected to this finishing method [(9),(10)].

2. Principle of the Electric Re-insulation Grinding Method

Figure 1 shows a diagram of the processing system used for the ERiG method. The anode and cathode of the electrolytic power supply are connected to the SMPC and to either the conductive grinding wheel or the electrode positioned with a gap between it and the conductive grinding wheel, respectively, and a current is applied. If the cathode is connected to the conductive grinding wheel directly, the conductive layer formed on the finished surface can be electrolytically removed in an efficient manner. On the other hand, if the cathode is connected to the electrode, this processing method can add the effect of ELID grind-

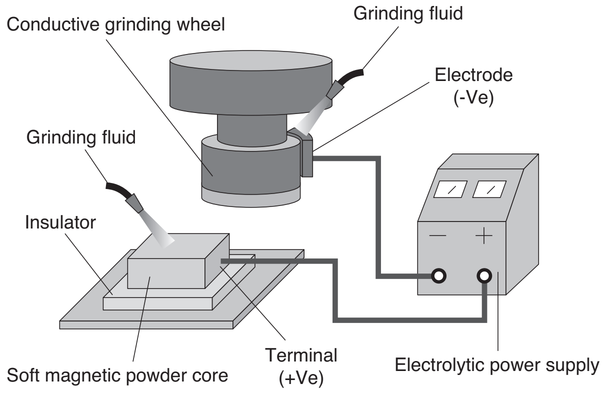


Fig. 1. Configuration of the electrolytic re-insulation grinding method

ing of the SMPC while electrolytically removing the conductive layer. To ensure the efficient electrolytic removal of the conductive layer, a conductive grinding fluid is applied between the SMPC and the conductive grinding wheel, and between the conductive grinding wheel and the electrode. In addition, as the SMPC needs to be insulated from the processing system, an alumina plate is used for this purpose.

The principle of this ERiG method is described using the diagrams shown in **Fig. 2 (1) to (4). (1)** As described earlier, the surface of the SMPC before finishing (compacting) is made up of pure iron powder covered with an insulation layer. The grain boundaries of the iron powder particles are clear, and the electrical resistance of the SMPC is high due to the effect of the insulation layer. (2) The ground surface of the SMPC is void of an insulation layer, and a conductive layer with unclear grain boundaries is formed on the surface due to the elastic deformation of surface particles subjected to processing stress, resulting in a significant decrease in electrical resistance. (3) As a current passes between the SMPC and the conductive grinding wheel during spark-out grinding, the pure iron conductive layer exposed from the finished surface is dissolved and ionized. The grinding fluid is also electrolyzed and produces hydroxyl radicals. (4) The conductive layer on the surface is removed by electrolysis. When electrolysis proceeds further, iron ions and hydroxyl radicals bond to form an iron hydroxide nonconductive layer on the finished surface of the SMPC, with the result that electrical resistance increases again.

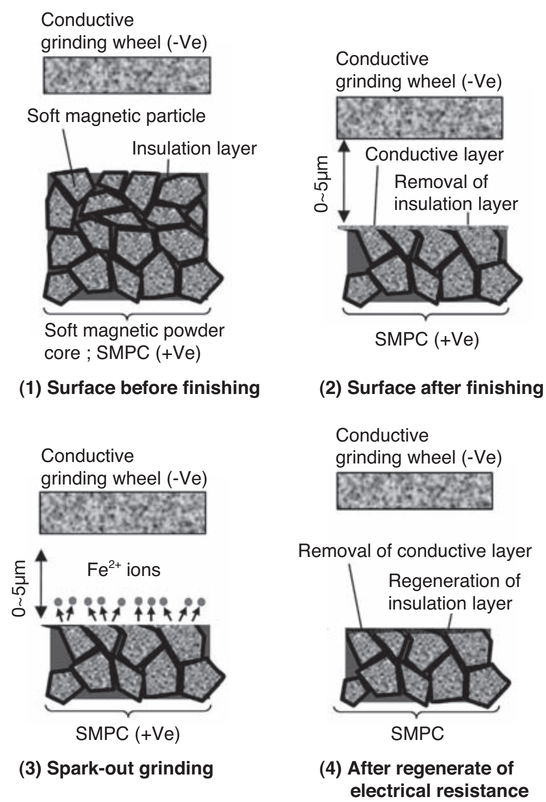


Fig. 2. Principle of the electrolytic re-insulation grinding method

3. Effect of Finishing on the Electromagnetic Conversion Efficiency of SMPCs

3-1 Procedure

Toroidal materials with an outer diameter of 34 mm, an inner diameter of 20 mm, and a thickness of 5 mm were used for the evaluation. Test piece A-1 formed into a toroidal shape simply by powder compacting, and test piece A-2 produced by finishing a block-like material to the same dimensions by conventional grinding using a general grinding wheel were prepared. **Table 1** shows the test conditions. A surface resistivity meter manufactured by Dia Instruments Co., Ltd. was used for electrical resistance measurements, and an AC magnetic characteristic evaluation device manufactured by METRON Technology Research, Inc. was used for iron loss characteristic measurements. Here, the iron loss characteristic is an index of the electrical energy lost during the process of AC electromagnetic conversion shown in units of power to weight, and the smaller the value, the better the electromagnetic conversion efficiency.

Table 1. Conditions for the preparation of toroidal test pieces

Item	A-1 (powder compacted)	A-2 (conventional grinding)
Density	7.5×10^3kg/m^3	7.5×10^3kg/m^3
Grinding wheel	NA	#80 PA
Grinding fluid	NA	Oil
Peripheral velocity	NA	1,800 m/min.
Wheel feed rate	NA	2 mm/min.

3-2 Evaluation results of electrical resistance and iron loss characteristics

The measured post-processing electrical resistances of test piece A-1 and test piece A-2 were 580 μΩm and 43 μΩm, respectively. **Figure 3** shows the iron loss characteristic for each test piece at different evaluation frequencies.

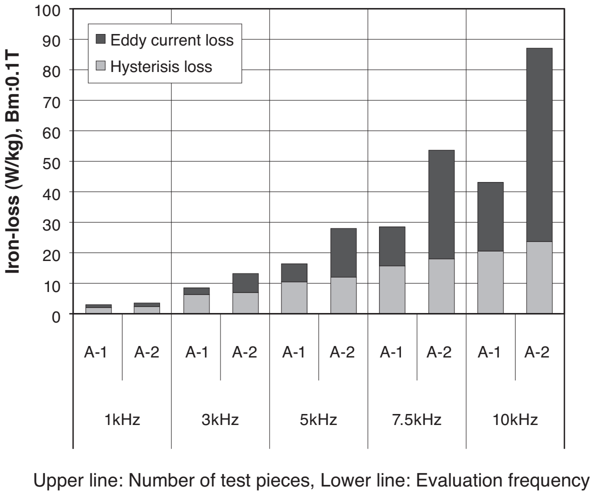


Fig. 3. Iron loss characteristics at different frequencies

The figure clearly shows that the iron loss characteristics increase as the frequency increases, and that the iron loss characteristics for test piece A-2 are higher than those for test piece A-1. Here, the hysteresis loss in the figure is attributable to the coercive force of the material, and increases in proportion to the frequency. The eddy current loss is ascribable to the electrical resistance of the material, and increases in proportion to the square of the frequency. Electrical resistance can therefore be said to be the most important characteristic because the eddy current loss shows a considerable increase as the frequency rises. These test results reveal the issue that when a SMPC is finished using a conventional grinding method, its electrical resistance drops to 1/10, and its iron loss characteristic at least doubles in the high frequency range.

3-3 Study on the cause of reduced electrical resistance

One of the causes of the reduced electrical resistance resulting from conventional grinding is the exposure of pure iron with low electrical resistance on the processed surface from which the insulation layer was removed. **Figure 4** shows SEM images of the surfaces and cross sections of test pieces A-1 and A-2. The grain boundaries of pure iron powder are clearly visible on the surface of the SMPC before processing in **Fig. 4 (a) and (b)**, whereas individual grain boundaries are not identifiable on the processed surface shown in **Fig. 4 (c) and (d)**. In addition, a conductive layer formed by adjacent pure iron particles can be seen through careful observation of the outermost surface layer shown in **Fig. 4 (d)**. These observation results led us to the conclusion that the electrical resistance of the SMPC significantly decreased due to conventional grinding, and this resulted in a significant drop in electromagnetic conversion efficiency.

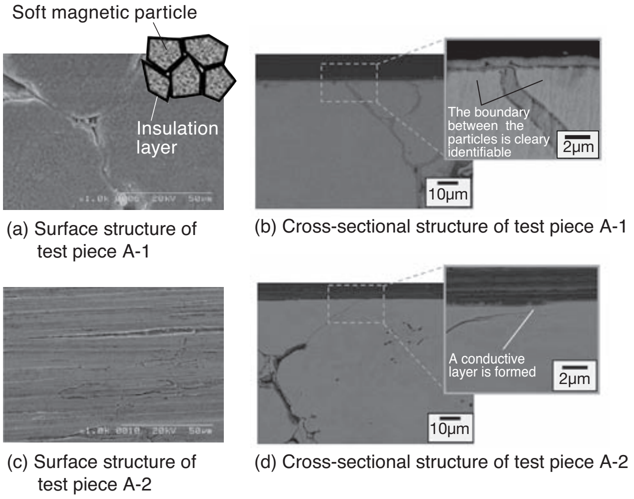


Fig. 4. SEM images of test pieces

4. Development of Finishing Method that Regenerates Electrical Resistance

4-1 Procedure

For the test, 30 x 20 x 15 mm square pillar shaped SMPCs were used to prepare test piece B-1 with a surface finished using the ERiG method, and test piece B-2, which was prepared using the same grinding wheel but not subjected to the removal of the conductive layer by applying a current.

Figure 5 shows an external view of the ERiG system used for the test. The authors developed this grinding system by connecting an electrolytic power supply manufactured by The NEXSYS Corporation to a vertical machining

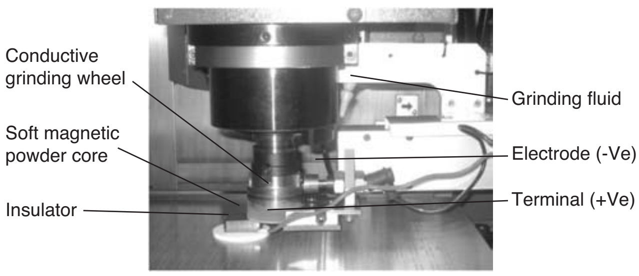


Fig. 5. Electrolytic re-insulation grinding system

Table 2. Conditions for ERiG method and conventional grinding method

Item	B-1 (ERiG)	B-2 (conventional grinding)
Grinding wheel	#325 metal bond CBN wheel	#325 metal bond CBN wheel
Grinding fluid	Water based	Water based
Peripheral velocity	900 m/min.	1,800 m/min.
Wheel feed rate	1 mm/min.	2 mm/min.
Electrolytic voltage	90 V	NA
Electrolytic peak current	10 A	NA
Pulse timing (on/off)	1/1 μs	NA

center manufactured by Mori Seiki Co., Ltd. The cathode of the grinding system feeds power from the SUS electrode to the grinding wheel through the gap. The test and electrolysis conditions are shown in **Table 2**.

4-2 Evaluation results and discussion

Figure 6 shows the measured electrical resistances of the finished surfaces of the test pieces. It is clear from the figure that the electrical resistance of test piece B-1 after ERiG is almost equal to the level before grinding. On the other hand, the electrical resistance of test piece B-2 finished using the conventional grinding method decreased considerably to approximately 1/6 of the level before grinding. According to the latest experimental data, it enables to get high electrical resistance such as over 5000 μΩm. Finally, the measured iron loss characteristics of the test pieces are shown in **Fig. 7**. This figure proves that there is little difference between the iron loss characteristics before and after grinding for test piece B-1 manufactured using the ERiG method. Contrary to this, the iron loss characteristic for test piece B-2 produced using the conventional grinding method is almost triple the level before grinding. This is attributable to a significant decrease in the electrical resistance of test piece B-2. From these results it can be concluded that the developed ERiG method is an effective finishing method that does not reduce electromagnetic conversion efficiency of SMPCs.

Figure 8 shows the results of an ESCA (Electron Spectroscopy for Chemical Analysis) analysis performed in the depth direction from the finished surface on test piece B-1 ground using the ERiG method in order to verify the principle of re-insulation the authors propose. In test piece B-1, oxygen (O) was detected to a depth of approximately 100 nm. The authors had already verified that, on SMPCs finished using conventional grinding, oxidation layers are only formed on the outermost surface layers, and accordingly assumed that Fe-O compounds were formed on the surface of test piece B-1.

The bonding state of Fe was also analyzed in depth using scattered electron Mossbauer spectroscopy. In this study, CEMS (Conversion Electron Mossbauer Spectroscopy) method was applied. **Figure 9** shows the measured Fe spectrum and **Fig.10** shows the fitted curve. And **Table 3** shows the result of analysis. Judging from the Fe spectrum measured, bonding between Fe and O was considered to be Ferrihydrite, and the formation of iron hydroxides was observed on the finished surface.

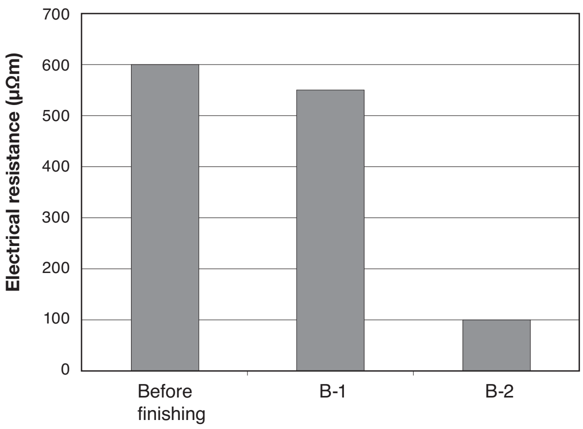


Fig. 6. Electrical resistance of finished surfaces

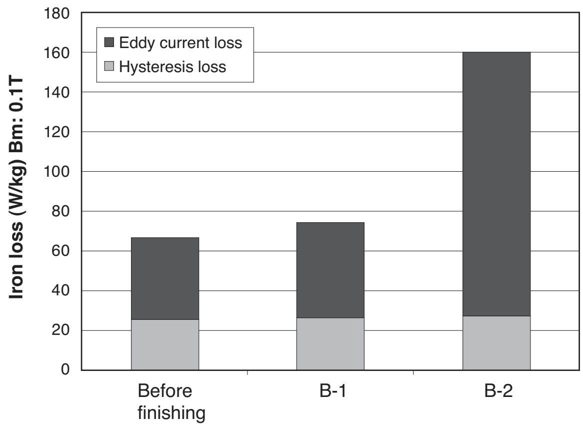


Fig. 7. Iron loss characteristics

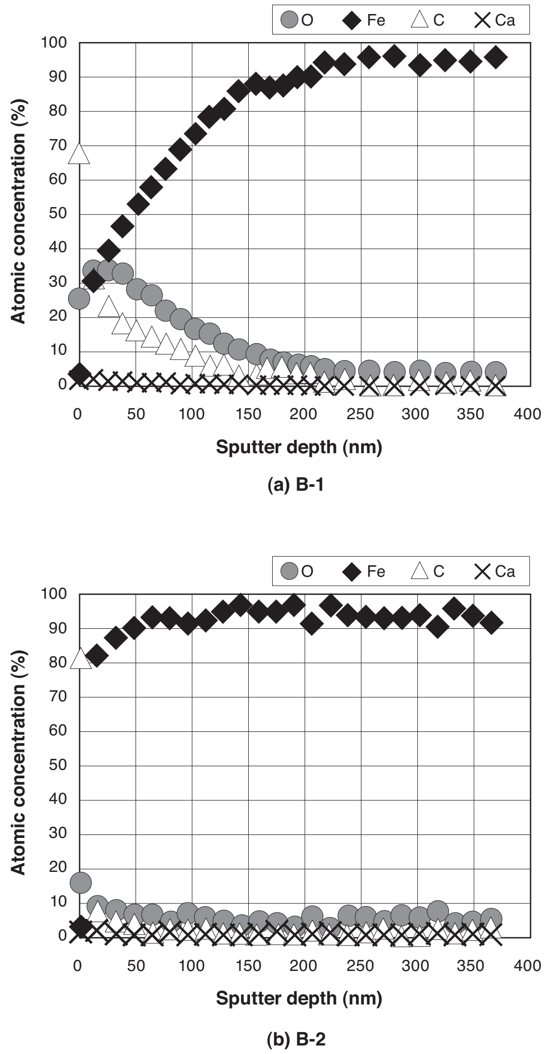


Fig. 8. ESCA analysis results of the surface of test piece B-1 ground using ERiG

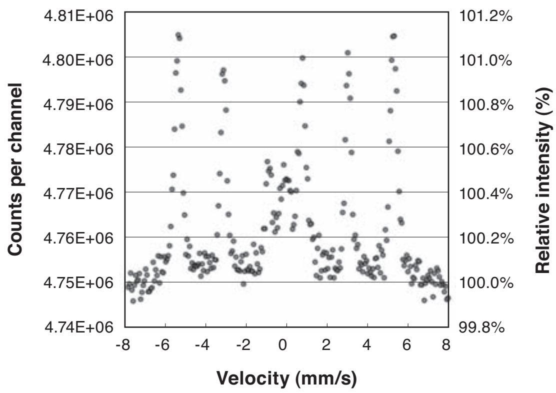


Fig. 9. CEMS analysis results of the surface of test piece B-1 ground using ERiG

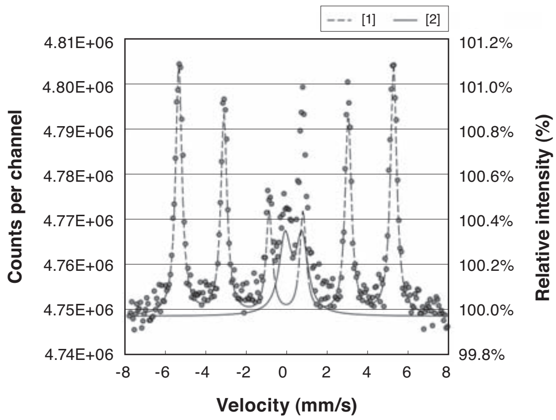


Fig. 10. Fitted curve

Table 3. Result of analysis

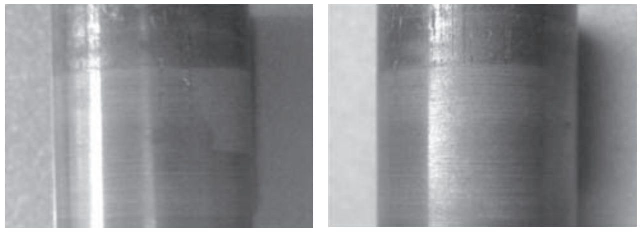
Item		δ (mm/s)	Δ (mm/s)	H (kOe)	Results of analysis
	[1]	+0.01	+0.00	324	α-Fe
	[2]	+0.38	0.84	0	Shown as table 4 in details

Table 4. Mossbauer parameter (11),(12)

Chemical formula	δ (mm/s)	Δ (mm/s)	H (kOe)
β-FeOOH (7)	+0.38	0.55	–
	+0.37	0.95	–
γ-FeOOH (7)	+0.37	0.53	–
Ferrihydrite (8)	+0.35	0.95	–

5. Anti-rust Effect on the Finished Surfaces Using ERiG Method

Figure 11 shows the appearance of finished surfaces using ERiG method. **Figure 11 (a)** shows the appearance immediately after the finishing by ERiG method. **Figure 11 (b)** shows the appearance after 6 months, and there is no rust on the finished surface. It is clear that the finished surface using the ERiG method has good anti-rust efficiency.



(a) Just finished (b) After 6 months

Fig. 11. Appearance of finished surfaces using ERiG method

6. Conclusions

The authors developed the ERiG method as a new finishing method for SMPCs. This method enables the finishing of SMPCs without compromising their excellent electromagnetic conversion efficiencies. Described below are the conclusions of this research.

1. The iron loss characteristics of SMPCs increase considerably if they are finished using conventional grinding methods. This is due to the formation of conductive layers on the outermost layers of finished surfaces resulting in significant decreases in electrical resistance.
2. The ERiG method grinds SMPCs while applying a current between SMPCs connected to the anode and the electrode positioned with a gap between it and the conductive grinding wheel to the cathode. This grinding method makes it possible to remove conductive layers formed on the finished surfaces of SMPCs and, at the same time, re-form nonconductive layers removed by grinding. These nonconductive layers consist of iron hydroxides.
3. SMPCs finished using the developed ERiG method maintain the high electrical resistances equal to the level before grinding. As a result, iron loss characteristics are also equivalent to pre-grinding levels, and can be reduced to approximately 1/3 of the level by conventional grinding methods.
4. The finished surfaces using the ERiG method have good anti-rust efficiency.

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