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Magnetic Properties and Workability of Fe-Si Alloy Powder Cores

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Fe-6.5% Si alloys have good magnetic properties due to their high electrical resistivity, very low magneto-striction, and low crystalline anisotropy. Despite their strong potential, these alloys have seldom been used in magnetic applications because of the very poor ductility of Si-steel above 3.0 wt% Si [1-4]. It is difficult to achieve compressed Fe-6.5% Si powder cores with excellent properties because of the low density due to poor ductility. In compressed powder cores, high density is essential in order to obtain high magnetization and permeability. In this study, an attempt was made to produce Fe-3%Si powder cores because the Fe-3.0 wt% Si alloys have relatively good magnetic properties and room temperature ductility. Gas atomized Fe-3.0 wt% Si powder was compressed into toroid shape cores. By reducing the Si content to 3.0 wt%, the hysteresis loss could be greatly reduced and thus the total core loss could be minimized. The total core loss is 600 mW/cm^3 at 0.1 T and 50 kHz.

Keywords: Fe-Si, powder core, core loss, ductility

1. Introduction

Silicon steels containing about 3.0 wt% Si are widely used as core materials in transformers, magnetic amplifiers and many other electronic devices. Also, at about 6.5 wt% Si, magneto-striction (λ) and crystalline anisotropy (K) can be optimized to achieve a lower core loss due to the higher permeability and lower coercivity (H_c) of the composition. However, the addition of silicon deteriorates the ductility of iron-base alloy. Therefore, the alloys with Si content higher than ~4 wt% become too brittle to be processed by the conventional rolling process at room temperature [1-4]. A number of researchers have reported that this can be overcome by using silicon-iron alloy powder cores [5, 6]. However, not enough studies have been carried out to show that silicon-iron alloy powder cores fully satisfy modern electronics requirements such as low core loss and good dc magnetic properties. In this study, we investigated the magnetic properties of Fe-3.0 wt% Si powder cores. The objective of this study was to commercialize silicon-iron alloy powder cores by utilizing PM techniques, to achieve a value lower than 600 mW/cm^3 at an induction of 0.1 T and 50 kHz, and to achieve an improved dc magnetic property over that of the Fe-6.5 wt% Si powder core.

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2. Experiments

Fe-3.0 wt% Si alloy powders with a spherical shape were prepared by a gas atomization process, and were then sieved until they could be classified at under 150 μm. These powders were annealed at 900°C in an N_2 gas atmosphere for 2 hours and then subjected to a wet coating process to form ceramic insulating layers. Toroidal cores (ϕ_{in} 14.6 mm, ϕ_{out} 26.8 mm, and H 11.1 mm) were produced under a high pressure of 1800 MPa and then heat treated at 730°C for 1 hour in a nitrogen atmosphere to reduce the press-induced internal stress. Effective permeability μ_{eff} was measured at 100 kHz by an impedance analyzer (HP4294A). Core losses of the powder cores were measured by an Iwatsu SY-8232 AC loop tracer under the conditions of 0.1 T and 50 kHz. The DC magnetic property was measured by an LCR meter (HP4284A) under the condition of 100 kHz.

3. Results and Discussion

Fig. 1 shows that the dc magnetic property of Fe-3.0 wt% Si powder core was higher than that of the Fe-6.5 wt% Si powder core. This may be due to the optimization of the insulation layer as well as the high magnetization and green density of Fe-3.0 wt% Si alloy. In order to understand the behavior of the increasing dc magnetic

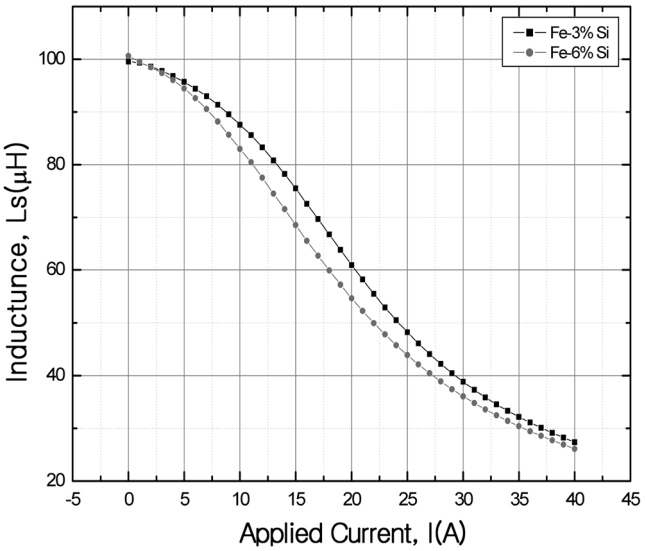

Fig. 1. DC magnetic property of Fe-Si alloy powder cores as a function of applied current.

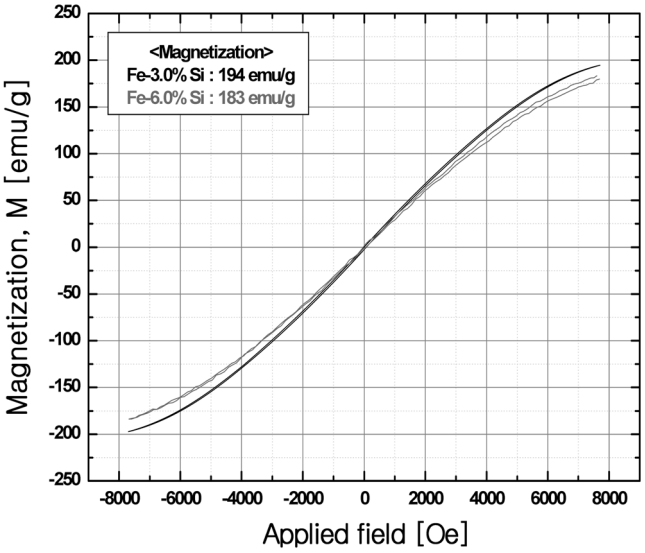

Fig. 2. Magnetization of Fe-Si alloy powder cores as a function of applied field.

property, magnetizations were obtained for Fe-3.0 wt% Si alloy that were higher than Fe-6.5 wt% Si, as shown in Fig. 2.

The Vickers hardness of Fe-3.0 wt% Si alloy powder (Hv = 135) is lower than that of Fe-6.5 wt% Si alloy powder (Hv = 350). A lower Vickers hardness for powder corresponds to a higher strain during the pressing process. Therefore, the green density (7.4 g/cm^3) of the Fe-3.0 wt% Si alloy powder core is higher than that of Fe-6.5 wt% Si (7.0g/cm^3).

Fig. 3 shows a comparison of the core loss of Fe-3.0 wt% Si (hysteresis loss (P_{hv}), the eddy current loss (P_{ev}),

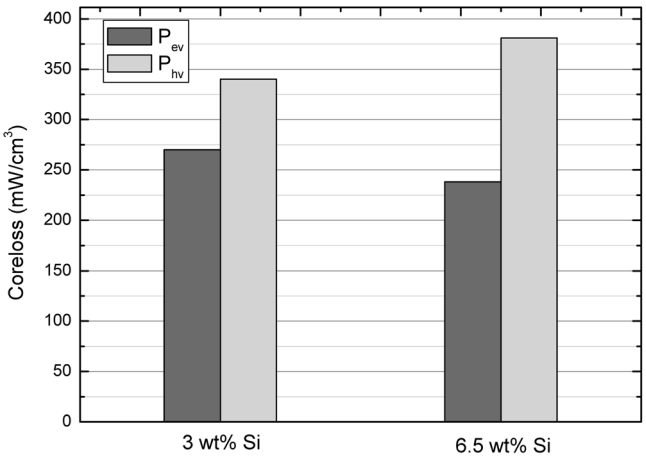

Fig. 3. Eddy current loss, Hysteresis loss of 3.0 wt%, 6.5 wt% Si-Fe powder cores.

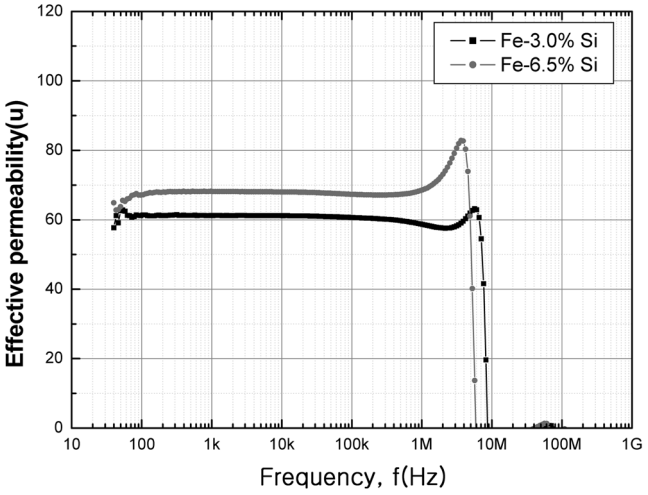

Fig. 4. Effective permeability of Fe-3.0 wt% Si powder cores as a function of frequency.

and the total loss ($P_{tot} = P_{hv} + P_{cv}$)) with the core loss of Fe-6.5% Si. In general, the hysteresis loss (P_{hv}) is inversely proportional to the green density [5, 6]. However, the eddy current loss of the powder core is not inversely proportional to the resistivity of the bulk material. Particle size is more important for the eddy current loss of powder core than the resistivity of bulk material [7, 8]. Thus, from the above trend, it can be deduced that the decreased total core loss of Fe-3.0 wt% Si core is mainly attributed to the increased green density.

Fig. 4 shows the frequency dependency of the permeability of Fe-3.0 wt% Si powder cores, the powder of which was annealed at 900°C for 2 hours in an N_2 gas atmosphere. An effective permeability, μ_{eff} of 65 is maintained up to 300 kHz. From the above results, it can be concluded that Fe-3.0 wt% Si powder cores can be commercialized.

4. Conclusion

In this study, Fe-3.0 wt.% Si alloy powder cores were successfully manufactured using gas atomization, annealing and coating processes. The total core loss could be minimized by reducing both hysteresis and eddy current loss, which were attributed to both a high green density and magnetization. An excellent core loss of 610 mW/cm^3 was achieved at an induction of 0.1 T and 50 kHz with suitable processes and an effective permeability μ_{eff} of 65 of the core at low frequency was maintained up to 300 kHz. These properties are comparable with the properties of well-known soft magnetic materials such as Fe-6.5%Si alloy. From the above results, it could be concluded that Fe-3%Si alloy powders have a high potential for commercialization.

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